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Design and simulation of tri-band circularly polarized antenna for radio navigation and ISM applications

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Dedication

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الملخص: يتناول هذا العمل تصميم ومحاكاة هوائي رقعة مدمج ثلاثي النطاق دائري الاستقطاب لتطبيقات الملاحة الراديوية و ISM. يستخدم الهوائي تقنية الرقعة المكدسة، مما يسمح له بتغطية نطاقات التردد (0.902-0.928) GHz للنطاق السفلي ISM، GHz (2.4-2.48) للنطاق الأعلى ISM، و (1.563-1.587) GHz لنطاق GP. يتم تحقيق الاستقطاب الدائري من خلال استخدام أربعة دبابيس للوصول إلى التغذية والتقنيات المشذبة، جنبا إلى جنب مع الفتحات. نظرًا لهيكله المستوي وحجمه المدمج (70 × 70 م2)، يمكن دمج هذا الهوائي دون عناء في أنظمة الاتصالات اللاسلكية المتنوعة. لتصميم هذا الهوائي استخدمنا CST MICROWAVE STUDIO.

الكلمات الرئيسية: Patch antenna, stacked, tri-band, circular polarisation, ISM, GPS, compact Size.

Abstract: This work deals with the design and simulation of a compact tri-band circularly polarized patch antenna for radio navigation and ISM applications. The antenna uses a stacked patch structure, which allows it to cover the frequency ranges of (0.902-0.928) GHz for ISM lower band, (2.4-2.48) GHz for ISM higher band, and (1.563-1.587) GHz for GPS band. Circular polarization is achieved through the use of four pin feed access and trimmed techniques, along with slots. Due to its planar structure and compact size (70 x 70 mm^2), this antenna could be effortlessly integrated into diverse wireless communication systems. For the design of this antenna we used CST MICROWAVE STUDIO.

Keywords: patch antenna, stacked, tri-band, circular polarisation, ISM, GPS, compact size.

Résumé : Ce travail traite de la conception et de la simulation d'une antenne patch tri-bande compacte à polarisation circulaire pour les applications de radionavigation et ISM. L'antenne utilise une structure de patch empilé, ce qui lui permet de couvrir les gammes de fréquences de (0,902-0,928) GHz pour la bande inférieure ISM, (2,4-2,48) GHz pour la bande supérieure ISM et (1,563-1,587) GHz pour la bande GPS. La polarisation circulaire est obtenue grâce à l'utilisation des techniques de troncature et alimentation à quatre broches d'accès, ainsi que des fentes. En raison de sa structure planaire et de sa taille compacte (70 x 70 mm2), cette antenne peut être intégrée sans effort dans divers systèmes de communication sans fil. Nous avons utilisé CST MICROWAVE STUDIO pour la conception de cette antenne.

Mots clés : antenne patch, empilée, tri-bande, polarisation circulaire, ISM, GPS, taille compacte.

Table of contents

List of abbreviations

2D: Two Dimensions.

3D: three Dimensions.

AR: Axial Ratio.

BW: Bandwidth

CAD: Computer Aided Design.

CP: Circular Polarization.

CST: Computer Simulation Technology.

EHF: Extremely High Frequency.

FIT: Finite Integration Technique.

GLONASS: Global Navigation Satellite System (in Russian).

GNSS: Global Navigation Satellite System.

GPS: Global Positioning System.

IEEE: Institute of Electrical and Electronics Engineers.

IOT: Internet Of Things.

ISM: Industrial, Scientific and Medical.

LF: Low Frequency.

MF: Medium Frequency.

HF: High Frequency.

LHCP: Left Handed Circular Polarization.

RHCP: Right Handed Circular Polarization.

MIMO: Multiple Input Multiple Outputs.

MWS: Microwave Studio.

PEC: Perfect Electric Conductor.

RFID: Radio Frequency Identification.

SHF: Super High Frequency.

SMA: Sub-Miniature version A.

UHF: Ultra High Frequency.

VHF: Very High Frequency.

VLF: Very Low Frequency.

WIFI: Wireless Fidelity.

List of figures

List of Tables

General introduction

In recent years, there has been an increasing demand for multi-band circularly polarized antennas that can cover both radio navigation and Industrial, Scientific, and Medical (ISM) applications. These applications require reliable and efficient communication systems that can operate in specific frequency bands while providing circular polarization for improved signal reception.

Radio navigation systems, such as Global Navigation Satellite Systems (GNSS) like GPS, GLONASS, and Galileo, are widely used for precise positioning, navigation, and timing. These systems operate in the L1 and L2 frequency bands, typically around 1.2 GHz and 1.6 GHz, respectively. On the other hand, ISM applications encompass a broad range of wireless communication systems used in industrial, scientific, and medical environments, with frequency bands such as 0.9 GHz and 2.4 GHz being commonly employed.

The design of a multi-band circularly polarized antenna capable of operating in both the radio navigation and ISM frequency bands poses significant challenges. It requires careful consideration of the antenna's dimensions, radiating elements, and feed structures to achieve the desired performance characteristics.

The advantages of circular polarization in these applications are twofold. Firstly, circularly polarized signals are less susceptible to multipath fading, providing improved signal reception and accuracy in radio navigation systems. Secondly, circular polarization offers enhanced immunity to polarization mismatch and interference in ISM applications, leading to more reliable and robust wireless communication.

The aim of this work is the design of a compact trainband circularly polarized antenna using printed technology. The designed antenna operates in three bands: radio navigation band [1.5-1.6] GHz, ISM lower band [0.902-0.928] GHz and ISM higher band [2.4-2.48] GHz and exhibits circular polarization. The obtained simulated results validate the good behaviour of the proposed antenna which meets the required technical specifications.

This dissertation is organized as follows:

The first chapter provides an overview of antennas (definition, history, applications, and key characteristics). Special attention is then given to printed antennas, their feeding techniques, and some of their advantages and disadvantages.

In the second chapter, we will explore the existing methodologies employed for achieving a multi-band antenna, along with the techniques used for circular polarization. This chapter is concluded by a scientific review on multi-band circularly polarized antennas, presented in tabular format, encapsulating pertinent details such as antenna geometry, dimensions, and operational frequency ranges.

The third chapter is exclusively dedicated to the design and electromagnetic simulation of printed antennas specifically engineered to operate within the following frequency ranges: GPS [1.5-1.6] GHz ,ISM frequency band (Wi-Fi) at [2.4-2.48] GHz and the lower ISM band at [0.902-0.928]GHz. After conducting a detailed examination, a comprehensive methodology is presented, along with a detailed analysis of the obtained results. Each technique used is explained meticulously, and the results are carefully examined and interpreted to meet the specified requirements. Finally, this chapter concludes with a thorough comparative analysis, comparing the antenna designed in this study with other established references. The aim of this analysis is to showcase the distinctive advantages and exceptional capabilities of the developed antenna.

Chapter 1: Fundamentals of Antennas

1.1 Introduction

Antennas assume a crucial and an indispensable role in facilitating the transfer of electromagnetic waves between transmitters and receivers in modern wireless communication systems; they play the role of a converter between one types of wave into another. Antennas come in different configurations, and find application in a broad range of fields. The use of antennas would make the wireless communication systems more operational, owing to the important function of this technology in multiple aspects of modern life. Given the continuous growth in demand for wireless communication services, antennas retain their significance in advancing and diversifying communication technologies. This chapter will present an overview of antennas, providing their definition, applications, their main characteristics and printed antennas in general.

1.2 Antennas: Definition, History and Applications

1.2.1 Definition

The conventional IEEE terminology for antennas (IEEE Std 145-1983) characterizes the antenna as a passive linear reciprocal contrivance [1]. It performs the task of an emitting antenna which is to guarantee the transfer of energy from a transmitter to the surrounding space where the energy can disseminate. Conversely, a receiving antenna is a mechanism that facilitates the transmission of energy from a wave traversing through space to a receiving device [2], as depicted in the figure 1.1.

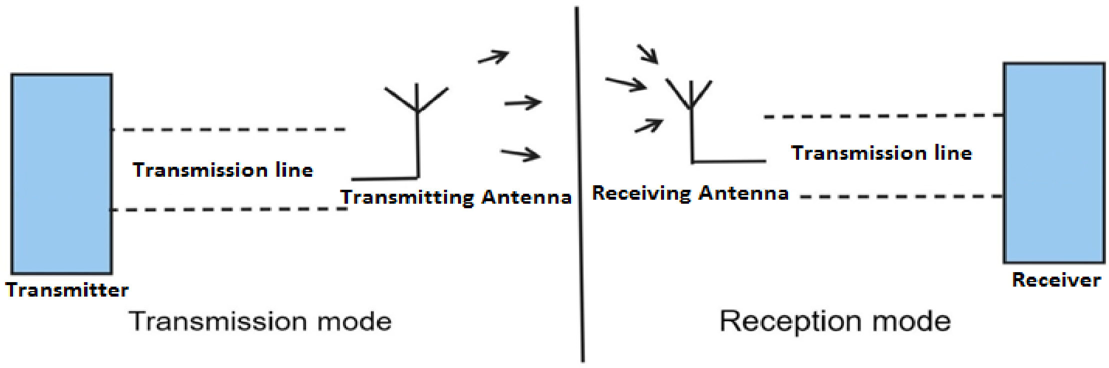


Figure 1.1. Antenna in transmission and reception mode

1.2.2 Brief history

In 1889, Heinrich Rudolf Hertz conducted an experiment aimed at verifying Maxwell's theory, during which he visually demonstrated the electric field lines emanating from a dipole antenna. He achieved this by employing two flat induction coils and a charged capacitor, creating a resonant electric circuit that produced a spark between the coils. The advent of radio communications is rooted in the electromagnetism theory that was formulated in the 19th century and refined in the 20th century; therefore, there were significant advancements in radio communications and antenna technology during this century [1].

1.2.3 Antenna applications

Antennas have a wide range of applications, especially in wireless communication; they serve the purpose of transmitting and receiving signals. They facilitate transmission of radio and television signals, aid GPS and navigation systems, and are integral to satellite communication, in additions to those applications are also used in scientific research, remote sensing, and biomedical applications and internet of thing (IOT).[3], [4]

a. Mobile communications

Some of the advantages are:

- Improve signal quality
- Increased range and coverage
- Multiple input multiple output (MIMO)
- Location –Based services

Overall, smart antennas are a key technology for improving the quality and reliability of mobile communication, and are widely used in various applications such 5G networks, IOT devices and mobile broadband services.

b. Radar systems

Some of the advantages of smart antennas in radar system are:

- Enhanced detection and tracking
- Adaptive Beam forming
- Multi-Target Tracking
- Radar imaging
- Radar communication

Smart antenna offer significant advantages in radar systems, they are widely used in various radar applications, such as military and defence, aerospace, meteorology, and automotive radar systems.

c. Internet of Things (IOT)

Smart antennas in IOT have several applications which encompass a network of interconnected devices that communicate and exchange data with each other. Some of the advantages of IOT are:

- Localization and tracking
- Smart home applications

Smart antennas offer significant advantages in IOT applications, which are used in multiple IOT deployments, such as smart cities, smart industries, and smart agriculture.

d. Medical applications

Some of the advantages are:

- Wireless medical monitoring
- Telemedicine
- Remote surgical assistance
- Emergency medical services
- Rehabilitation and physiotherapy

e. Satellite communications

Smart antennas are increasingly being used in satellite communication in different applications. Some of the advantages are:

- Improved Satellite link performance
- Satellite Broadband communication
- Earth Observation and Remote Sensing
- Navigation and Positioning Systems
- Satellite Broadcasting

Smart antennas are a key technology in modern satellite communication systems, enabling more reliable, efficient, and accurate communication with satellite.
The most common antennas applications According to frequency band are illustrated in figure1.2.

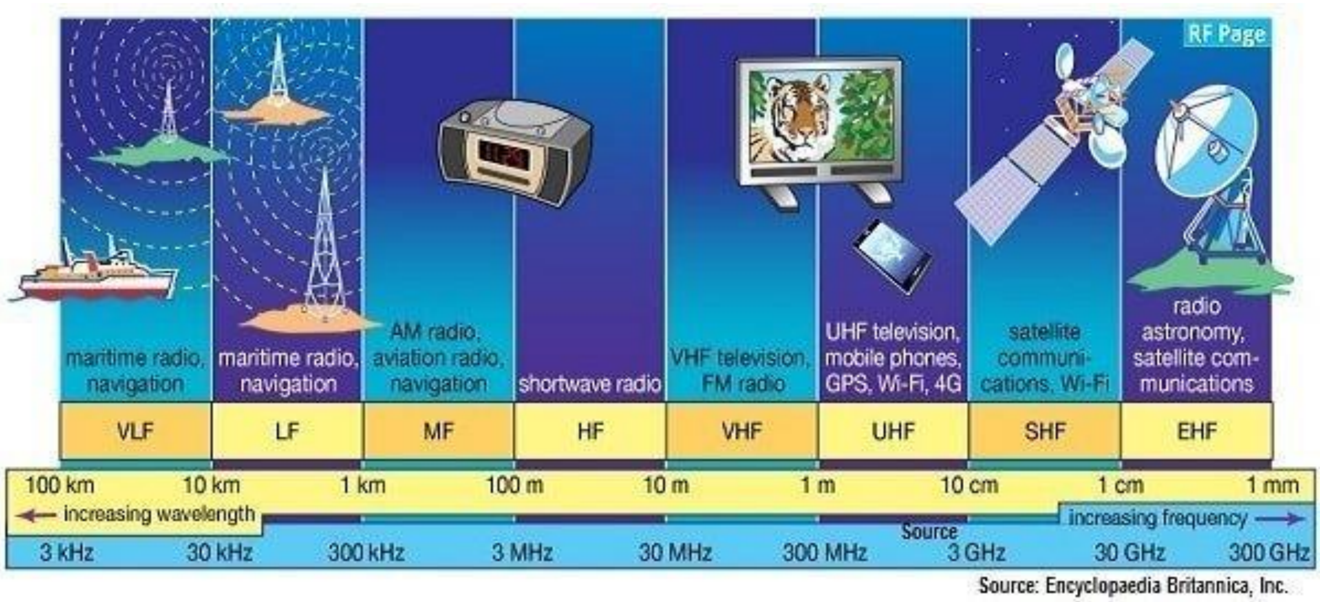


Figure 1.2. Some of antenna applications according to frequency band [4]

1.3 Principle characteristics of antennas

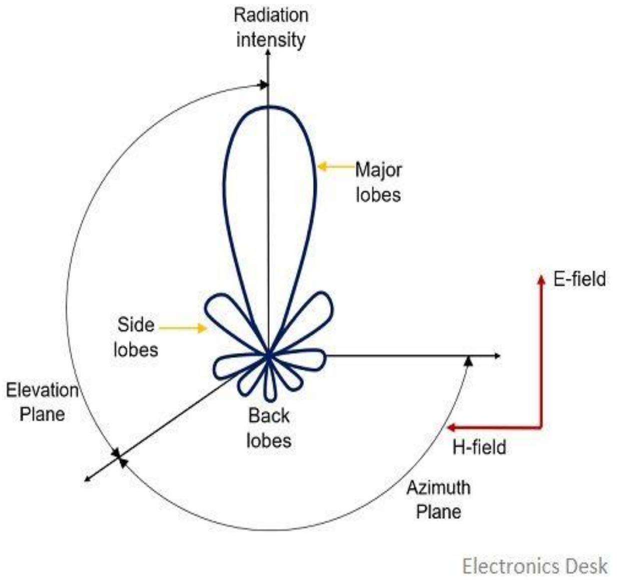
The main characteristics of an antenna are radiation pattern, directivity, gain, efficiency, polarization, impedance, reflection coefficient, and bandwidth.
These characteristics are important for selecting and designing an antenna for Specific application

1.3.1 Radiation pattern

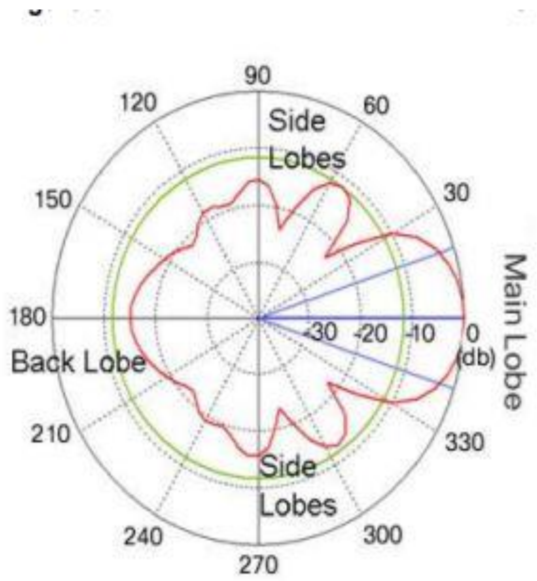
The directional behaviour of an antenna, as well as the amount of electromagnetic energy it radiates in different directions, is defined by its radiation pattern [5]. This pattern is typically presented as a 2D or 3D graph that displays the electromagnetic field's relative strength at various angles from the antenna. The radiation pattern is typically measured in the far field, where the electromagnetic waves are considered planar and is usually illustrated using a polar plot in either the azimuth or elevation plane[6].

Radiation patterns can be characterized as unidirectional or directional. An unidirectional pattern radiates equally in all directions, whereas a directional pattern concentrates the energy in a particular direction or directions. The directivity of an antenna describes its ability to concentrate energy in a particular direction and is related to the shape of the radiation pattern. Antennas with high directivity have a narrow beam-width, which is the angular width of the main lobe of the radiation pattern [7]. The beam-width is inversely proportional to the directivity, so antennas with high directivity have a narrow beam-width and antennas with low directivity have a wide beam width.

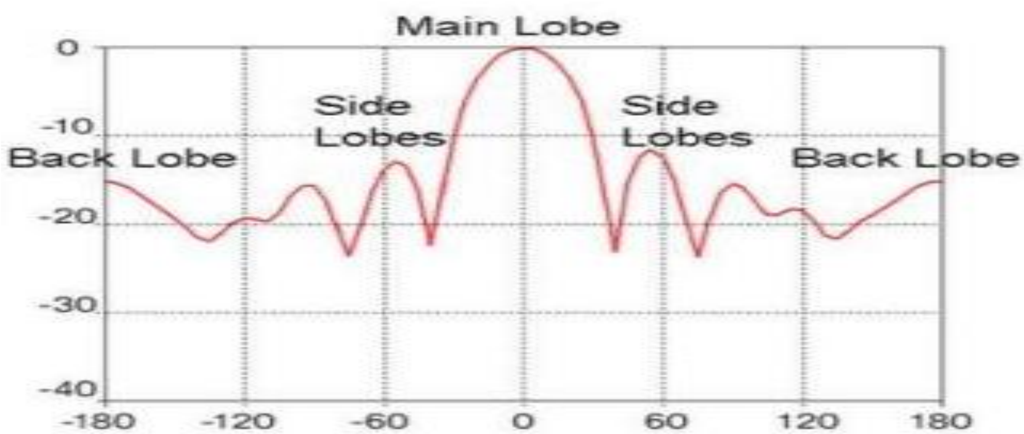
Radiation patterns are important for determining the coverage area of an antenna and for minimizing interference with other nearby antennas. They are also important for determining the directionality and signal strength of a wireless communication link [8]. Some of examples of radiation pattern are illustrated by figure 1.3



(a)



(b)



(c)

Figure 1.3. Radiation pattern: (a) view 3D, (b) view 2D (Polar Coordinates), (c) view 2D (Cartesian Coordinates) [8]

1.3.2 Directivity

The directivity of an antenna can be described as the relationship between the intensity of radiation emitted in a particular direction and the average radiation intensity across all directions (as emitted by an isotropic antenna). This average radiation intensity is equivalent to the total power radiated by the antenna, divided by 4π [9].

The directivity is represented by the following equation:

$$\boldsymbol{D} = \frac{\boldsymbol{U}}{\boldsymbol{U}_0} = \frac{4\boldsymbol{\pi}\boldsymbol{U}}{\boldsymbol{P}_{\mathrm{ra\gamma}}} \quad (1.1)$$

Where:

D: directivity

U_0 :radiation intensity of isotropic source.

U: radiation intensity

P_{rad}: radiation power

1.3.3 Gain

The gain of an antenna is a crucial parameter that determines its performance and effectiveness. It is a measure of how much the signal power is increased by the antenna in a specific direction, in comparison to the power that an ideal isotropic antenna, radiating the same total power, would produce [9]. This measure is typically expressed in decibels (dB), and it is calculated as the ratio of the radiation intensity in a specific direction to that of an isotropic radiator**.**

$$\boldsymbol{G} = \frac{4\boldsymbol{\pi}\ \boldsymbol{U}}{\boldsymbol{P}_{\boldsymbol{in}}} \quad (1.2)$$

Where:

G: Gain

U: radiation intensity

P_{in}: accepted antenna power

1.3.4 Efficiency

Determining the efficiency is one of the fundamental steps in quantifying the performance of an antenna. This parameter represents the amount of power actually radiated by the antenna compared to the input power to the same antenna [9]. For a given direction, the ratio of the antenna gain (G) to the directivity (D) also gives the efficiency for that direction.

$$\eta = \frac{\boldsymbol{G}}{\boldsymbol{D}} \quad (1.3)$$

Where:

η:Efficiency

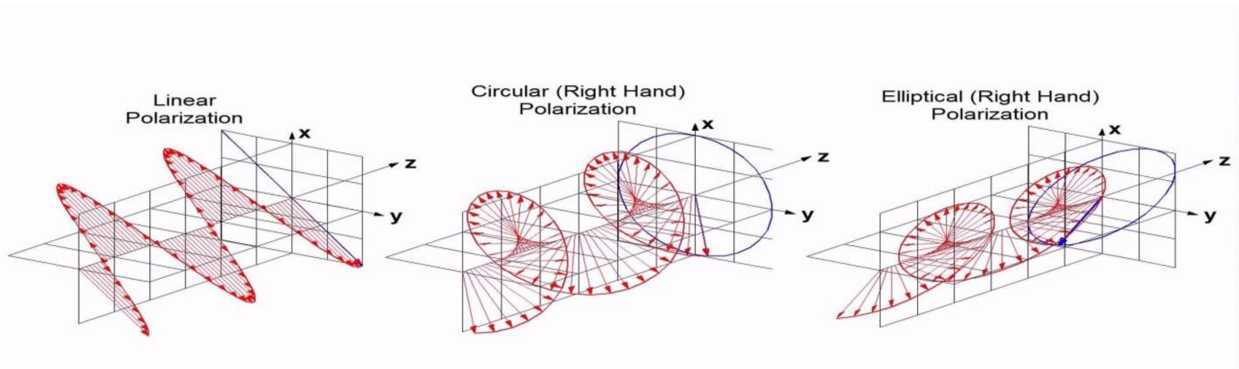
G: Gain

D: Directivity

1.3.5 Polarization

The polarization of a wave is a fundamental parameter for the study of antennas [5]. Indeed, depending on the structure of the antenna, which will only receive a certain type of polarization. Therefore, if the polarization of the receiving antenna is not matched to the polarization of the transmitting antenna, the received power will not be maximum. There are several types of polarization, namely linear, circular, and elliptical.

Some examples are illustrated by figure 1.4.



(a) (b) (c)

Figure 1.4. Polarization (a) linear, (b) circular, (c) elliptical [5]

1.3.6 Input impedance

The input impedance of an antenna **Zin** is the impedance at its input [9] and it is given by:

$$Z_{in} = R_A + jX_A \quad (1.4)$$

Where:

- **R_A:** Input resistance which represents a term of dissipation. It is linked, on the one hand to the radiated power and on the other hand, to the power lost by Joule effect.

- **X_A:** The reactance of the antenna which is linked to the reactive power stored in the vicinity of the antenna.

The antenna impedance is affected by surrounding objects, in particular by metallic objects or other nearby antennas [9].

An antenna powered by a generator is shown in figure 1.5.

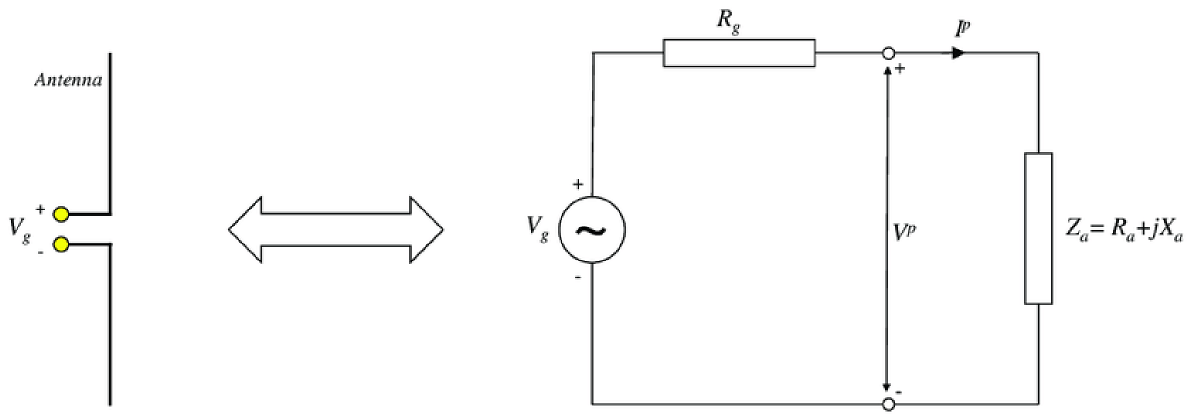


Figure 1.5. Equivalent circuit representation of an antenna [6]

1.3.7 Reflection coefficient

The reflection coefficient is a measure of the antenna's ability to transfer power to a transmission line or to free space. When an antenna is connected to a transmission line or a waveguide, some of the energy from the line is transmitted to the antenna, and some is reflected back towards the line [5]. The reflection coefficient **Γ** (or **S_{11}**) is given by:

$$\Gamma = \frac{Z_{\text{in}} - Zc}{Z_{\text{in}} + Zc} \qquad (1.5)$$

Where:

Z_{in}: input impedance. **Zc:** line characteristic impedance.

In general we accept that a goodmatching is achieved for a reflection coefficient lower than -10 dB.

1.3.8 Bandwidth

The term antenna bandwidth (BW) pertains to the frequencies within which an antenna can efficiently send and receive signals [9]. This range is usually described as the frequencies lying between the upper and lower limits, within which the antenna can perform within specific predetermined parameters like gain, impedance, or radiation pattern. Having a wider bandwidth enables an antenna to operate over a larger range of frequencies, which can be advantageous in various applications such as communication systems, where different frequencies are utilized. Figure1.6. illustrates an example of a bandwidth.

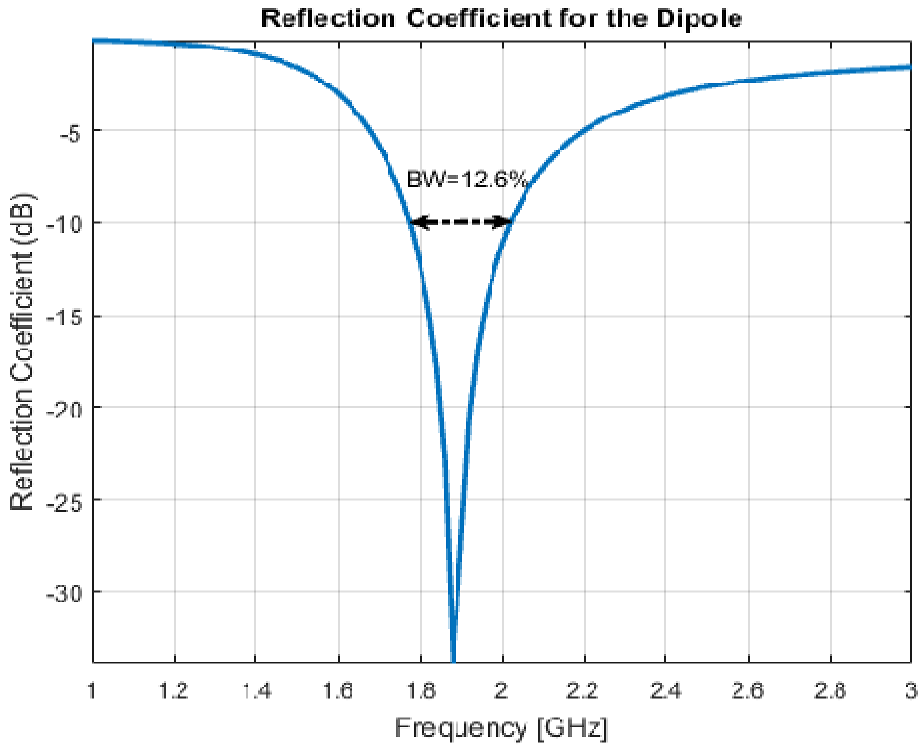
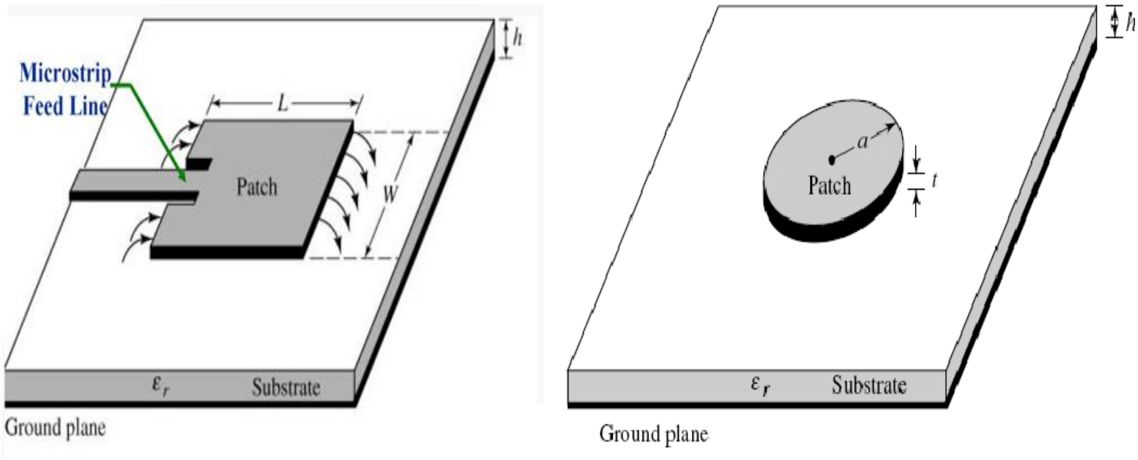


Figure 1.6. Example of antenna bandwidth [9]

1.4 Printed antennas

1.4.1 Definition

The planar antenna, or patch antenna, is a recent type of antenna whose development and use are becoming increasingly common. It is made up of a dielectric material characterized by a permittivity (ε_r) and thickness (h), with a metallic ground plane on one side. On the other side, a metal engraving allows surface currents to support the electromagnetic radiation [6]. The currents are fed from the generator to the antenna by a micro-strip line. Patch antennas find extensive applications across various domains such as wireless communication systems, satellite communication, radar systems, and remote sensing. An example of patch antenna is illustrated by figure 1.7.



(a) **(b)**

Figure 1.7. Patch antenna: (a) rectangular, (b) circular [7]

1.4.2 Feeding techniques

Patch antennas can be fed using different techniques depending on the specific application and design requirements. Here are some common feeding techniques for patch antennas [6]:

a. Micro-strip line feed

This is the most common feeding technique for patch antennas[10]. A micro-strip line is used to feed the patch antenna, which is located at a specific distance from the patch antenna. The feed point is generally located at the centre of the patch antenna, and the feed line is connected to the patch through a small gap. The micro-strip line feed is shown in figure 1.8.

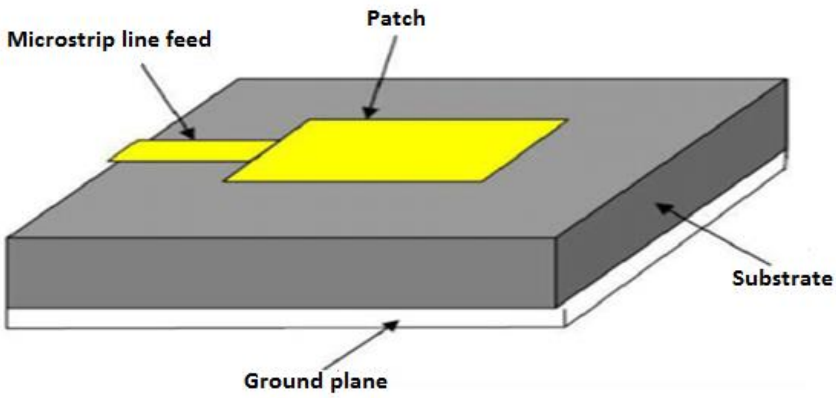


Figure 1.8. Micro-strip line feed [10]

b. Proximity coupled feed

In this technique, the patch antenna is fed by placing the feed element near the edge of the patch antenna [9]. The feed element can be a metallic strip, loop or other shapes, and it is placed parallel to the patch antenna. The distance between the patch antenna and the feed element determines the coupling between them. Proximity coupled feed is shown in figure 1.9.

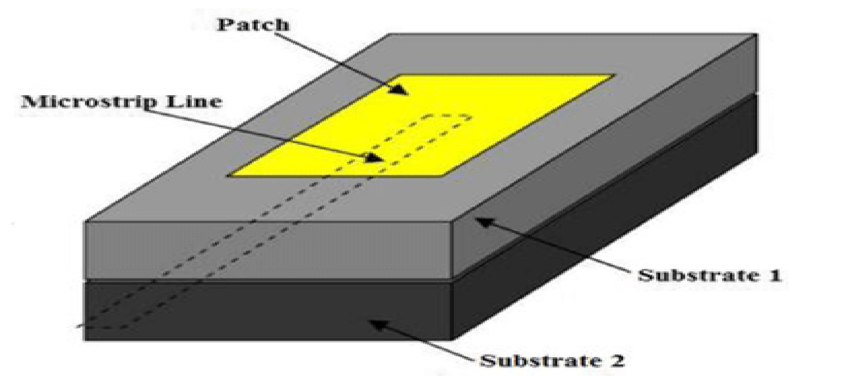


Figure 1.9. Proximity coupled feed [9]

c. Aperture coupled feed

In this technique, a slot is made on the ground plane beneath the patch antenna [10], and the feed is coupled to the patch through the slot. The slot acts as a waveguide that guides the signal to the patch antenna. This technique offers a high degree of isolation between the feed and the patch, making it suitable for applications that require good isolation. Aperture coupled feed is shown in figure 1.10.

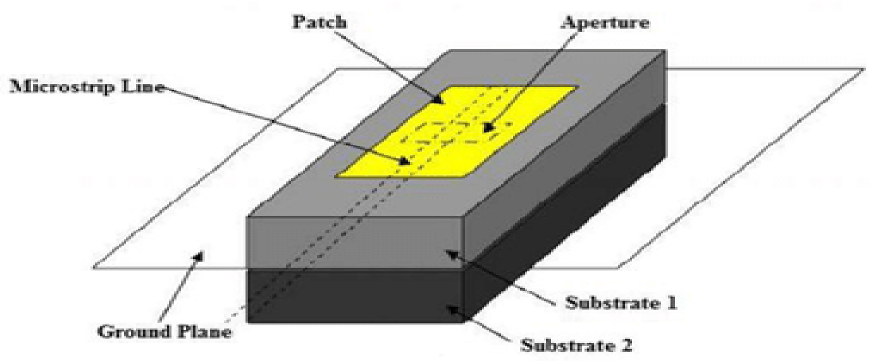


Figure 1.10. Aperture coupled feed [10]

d. **Coaxial feed**

One approach for feeding a patch antenna is through the use of a coaxial cable [10], where the centre conductor is linked to the patch antenna, while the ground plane is connected to the outer conductor. This method is known for its ease of implementation and capability to provide effective impedance matching. Coaxial feed is shown in figure 1.11.

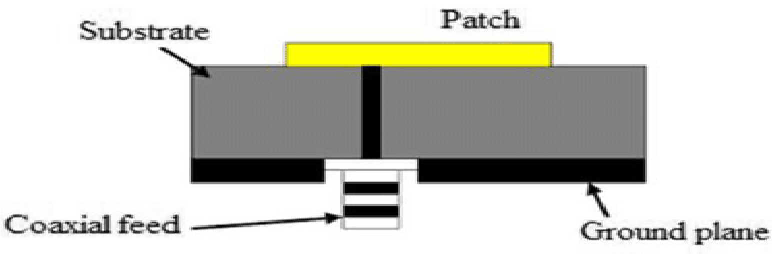


Figure 1.11. Coaxial feed [10]

1.4.3 Advantages and disadvantages of printed antennas

Printed antennas, also known as micro-strip antennas, offer several advantages and disadvantages compared to traditional wire antennas. Cite some of them [11]:

- **Advantages**

  - Low Profile: Micro-strip antennas have a low profile and are flat, making them easy to integrate into various types of devices and systems without adding significant weight or bulk.
  - Lightweight: Due to their low profile and use of lightweight materials, micro-strip antennas are lightweight, making them ideal for applications that require a lightweight design.
  - Low Cost: Micro-strip antennas can be manufactured using low-cost materials and fabrication techniques, making them a cost-effective option for many applications.
  - Wideband Operation: Micro-strip antennas can operate over a wide frequency range, making them suitable for applications that require a broad operating bandwidth.
  - Directionality: Micro-strip antennas can be designed to have a directional radiation pattern, which makes them ideal for point-to-point communication applications.

- Easy to Design: Micro-strip antennas are relatively easy to design and analyze using computer-aided design tools, allowing for rapid prototyping and optimization.
- Compatibility with Planar Circuits: Micro-strip antennas can be integrated with other planar circuits, such as filters and amplifiers, to form highly integrated systems.

- **Disadvantages**
  - Low Efficiency: Micro-strip antennas have lower efficiency compared to other types of antennas, such as horn antennas and parabolic reflector antennas, due to the significant power loss in the substrate and ground plane.
  - Narrow Bandwidth: This limits their use in applications that require a wide operating bandwidth.
  - Sensitivity to the Environment: The performance of micros-trip antennas can be affected by changes in the surrounding environment, such as temperature and humidity.
  - Surface Wave Generation: Micro-strip antennas can generate surface waves, which can lead to unwanted radiation and reduced antenna efficiency.
  - Limited Power Handling: Micro-strip antennas have limited power handling capability, which can be a concern in applications that require high power transmission.
  - Low Radiation Efficiency: Micro-strip antennas have low radiation efficiency in the direction perpendicular to the substrate, which can lead to a low gain in that direction.

1.5 Conclusion

This chapter deals with the study of antennas by presenting their definition, a brief historical overview, and an exploration of their key applications and features. Particular attention has been devoted to examining the radio-electric and radiation characteristics of antennas. Additionally, significant emphasis has been placed on printed antennas, specifically patch antennas, due to their numerous advantages over traditional antennas. These advantages include low cost, compact size, and effortless integration.

Chapter 2: Scientific review on multiband circularly polarized antennas

2.1 Introduction

A circularly polarized multi-band patch antenna is a specialized antenna capable of operating in two or more distinct frequency bands while maintaining circular polarization. This antenna combines the benefits of multi-band operation, enabling compatibility with diverse frequency bands, and circular polarization, ensuring consistent signal reception regardless of the orientation of the receiving antenna. These antennas find widespread use in various wireless communication applications, including satellite communication, RFID systems, wireless networking, and mobile communication. They offer numerous advantages, including the ability to operate in two separate frequency bands, facilitating compatibility with multiple wireless standards and facilitating simultaneous transmission and reception across different frequency ranges. Additionally, their circular polarization characteristic ensures consistent signal quality by minimizing multipath interference and polarization mismatch. This chapter provides a comprehensive overview of circularly polarized multi-band patch antennas, beginning with an exploration of the techniques employed to achieve multi-band functionality and circular polarization. Furthermore, a non-exhaustive literature review is presented, showcasing notable contributions from the scientific community in this field.

2.2 Multi-band antenna techniques

To design a multiple band antenna, a diverse range of techniques can be used to facilitate its efficient operation across distinct frequency bands, demanding meticulous attention to a range of techniques and design elements. Herein, we present a compilation of several widely utilized techniques and commonly employed approaches for accomplishing the objective of designing a multiband patch antenna.

2.2.1 Trap Antennas

An old concept for achieving multi-band antennas is to embed discrete loads in an antenna, known as "traps"[12]. This concept is divided into two steps: the design of the resonant antenna at low frequency, then the introduction of loads to obtain the desired resonance at high frequency. The loads do not affect the low frequency or the characteristics of the antenna, but they cut off the high frequency current on the external parts of the antenna. The positions of the charges can be calculated easily for a monopole or a right dipole. The performance of these antennas depends on the hatches used and any manufacturing errors. High quality factor traps reduce antenna bandwidth. These antennas were mainly used in low-frequency systems, but the emergence of new, compact and high-performance elements at higher frequencies has recently revived interest in these trap-based concepts. An example of trap antennais illustrated by figure 2.1.

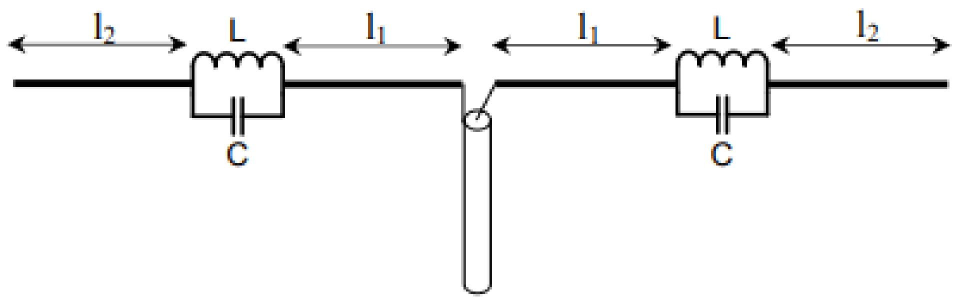


Figure 2.1. Dual band trapped antenna [12]

2.2.2 Stacked patch antenna

Constructing a multiband patch antenna involves stacking multiple patches on top of each other [13], with each patch specifically optimized for a particular frequency band. The stacked patches can be connected through a common feed line, where the same feed point is used for all the patches, or they can have independent feeding networks, with separate feed lines for each patch.

By carefully designing and adjusting the dimensions of each patch, they can resonate at different frequencies, thereby enabling multiband operation. The stacking arrangement allows for compact integration of multiple frequency bands within a single antenna structure. This technique is illustrated by figure 2.2.

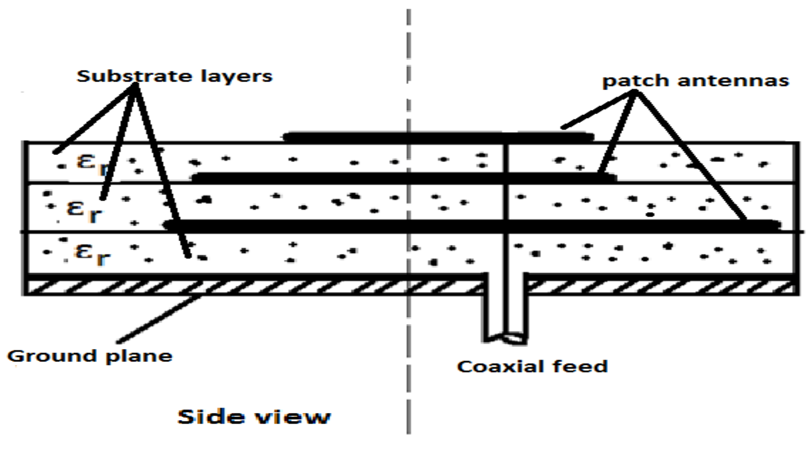


Figure 2.2. TribandStacked Patch Antenna [13]

2.2.3 Aperture-coupled patch antenna

Utilizing an aperture-coupled feeding mechanism involves incorporating a slot or aperture in the ground plane to couple energy to the radiating patch of an antenna[14]. This technique enables multiband operation by exciting multiple resonant modes.

By carefully adjusting the dimensions of the aperture and the feed line, different resonant frequencies can be achieved. The size and shape of the aperture play a crucial role in determining the coupling efficiency and the resonant characteristics of the antenna. By tuning these parameters, the antenna can be designed to resonate at multiple frequencies, thereby enabling multiband operation. This technique is illustrated by figure 2.3.

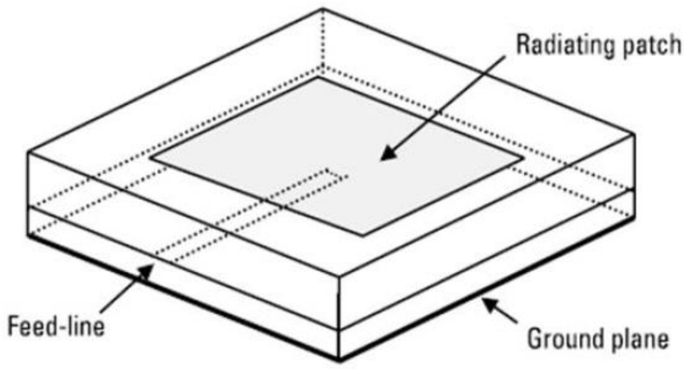


Figure 2.3. Aperture-Coupled feed technique [14]

2.2.4 Proximity-coupled patch antenna

Employing a proximity-coupled feeding technique involves placing the feed line close to the radiating patch without direct electrical contact[14]. This proximity coupling controls impedance matching and resonant behaviour, enabling multiband performance. It uses the electromagnetic field from the feed line to induce currents in the patch, optimizing impedance for different frequency bands. This technique offers benefits such as improved isolation, reduced losses, and enhanced bandwidth. Careful consideration is given to spacing, substrate properties, and feed line dimensions. Electromagnetic simulations help achieve desired multiband performance. Overall, proximity-coupled feeding allows for precise control without direct contact, facilitating efficient multiband operation in patch antennas. This technique is illustrated by figure 2.4.

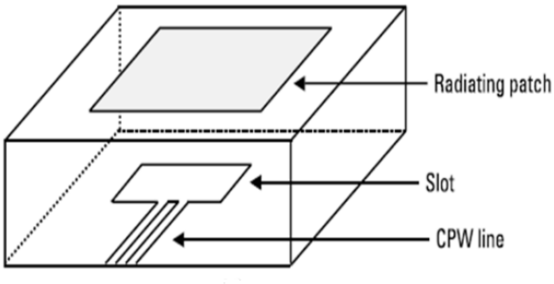


Figure 2.4. Proximity-Coupled feed technique [14]

2.2.5 L-shaped or U-shaped slots

Introducing L-shaped or U-shaped slots on the patch of an antenna creates additional resonant modes for multiband operation[15]. By adjusting the dimensions of the slots, different frequency bands can be targeted. These slots modify the electromagnetic field distribution and alter the effective electrical length of the patch, enabling resonance at desired frequencies. This technique offers design flexibility and allows the antenna to operate efficiently across multiple bands. Careful placement and dimension optimization are important for achieving desired resonant frequencies and impedance characteristics. Overall, L-shaped or U-shaped slots enhance the antenna's multiband capability by introducing additional resonances. An example of U-shaped slot is illustrated by figure 2.5.

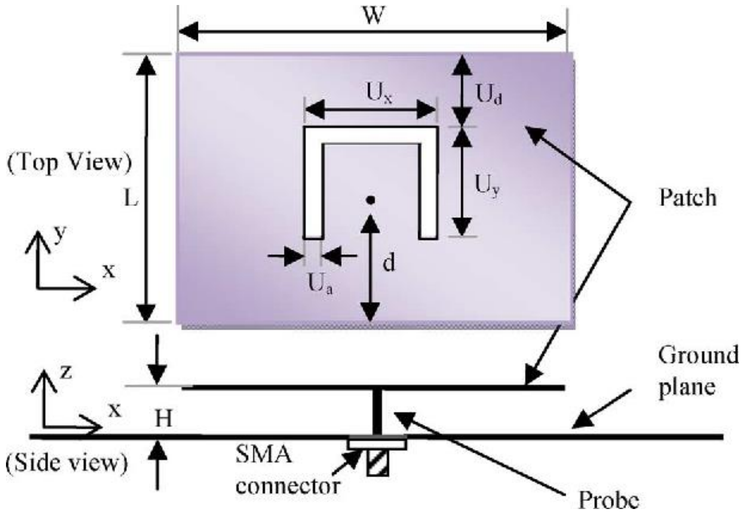


Figure 2.5. An example of U-shaped slot patched antenna for multiband [15]

2.2.6 Parasitic elements

Incorporating parasitic elements around the main radiating patch enables multiband operation in antennas [16]. These elements interact with the main patch, creating additional resonant modes and modifying its properties. By adjusting the dimensions and placement of the parasitic elements, the antenna can cover multiple frequency bands. Optimization and simulations are used to achieve desired resonant frequencies and impedance characteristics. This technique enhances design flexibility and expands the antenna's capability to support various frequency ranges. Figure 2.6 illustrates an example of this technique.

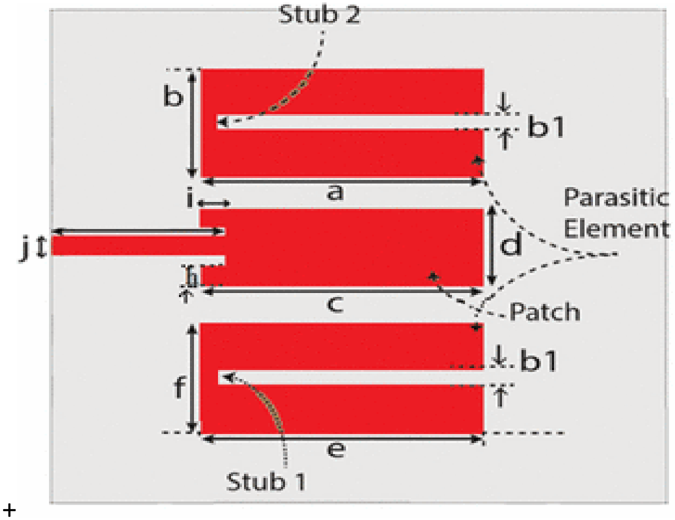


Figure 2.6. An example of parasitic element in patch antenna [16]

2.2.7 Resonant structures

The integration of resonant structures, such as meander lines, fractal geometries, or defected ground structures, within the antenna design enables multiband operation [17].These structures introduce additional resonant modes and expand the antenna's bandwidth, allowing it to cover multiple frequency bands. Precise design and optimization are crucial for achieving the desired resonant frequencies and impedance characteristics. This technique enhances the antenna's efficiency and enables it to operate effectively across a wide range of frequencies. An example of this technique is illustrated by figure 2.7.

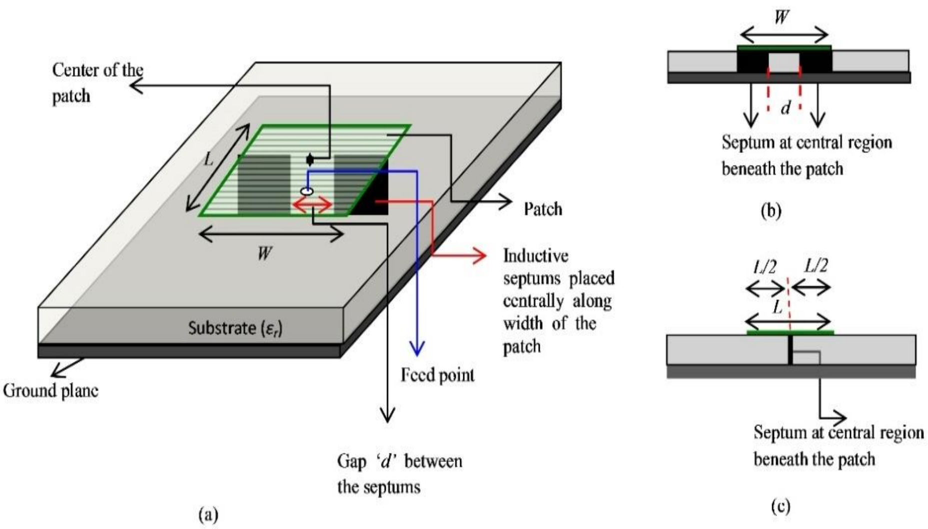


Figure 2.7. Rectangular antenna using Resonant Structures [17]

2.3 Circular polarization techniques

There are several techniques for producing circular polarized antennas. Here are some of the most commonly used techniques for planar antennas.

2.3.1 Circular patch antennas

This type of patch antenna consists of a circular patch element that is fed with two orthogonal modes. A shorting pin is used to excite the circular polarization [18]. The pin is placed at a specific distance from the centre of the patch to produce the desired circular polarization. The circularly polarized patch antenna is a popular choice for satellite communication systems. Figure 2.8 illustrates a shape of a circular patch.

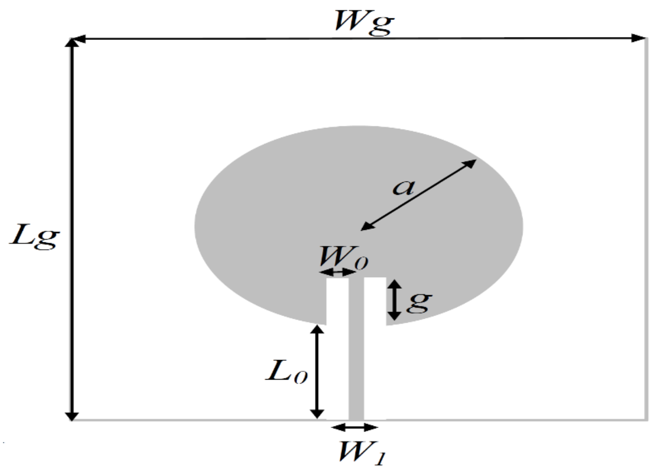


Figure 2.8. Circular Patch Antenna [18]

2.3.2 Crossed slots

Crossed slots can be cut into the patch element to produce circular polarization. The slots are oriented perpendicular to each other and fed with a 90-degree phase shift to produce circular polarization [19].

Crossed slots antennas consist of two orthogonal slots on a conductive plate or waveguide, allowing for unidirectional or broadside radiation patterns. The slots intersect at a right angle, and the antenna is typically fed through a coaxial cable or micro-strip line at the intersection point. The radiation pattern is symmetric and can be either linear or circular polarization. Crossed slots antennas offer wide bandwidth and find applications in wireless communication systems that require broad coverage, such as Wi-Fi, cellular networks, satellite communications, RFID systems, and radar systems [19]. Design considerations include slot dimensions, substrate material, feeding mechanism, and operating frequency range. Simulation tools and experimental testing help optimize the antenna's design and performance.This technique is illustrated by figure 2.9.

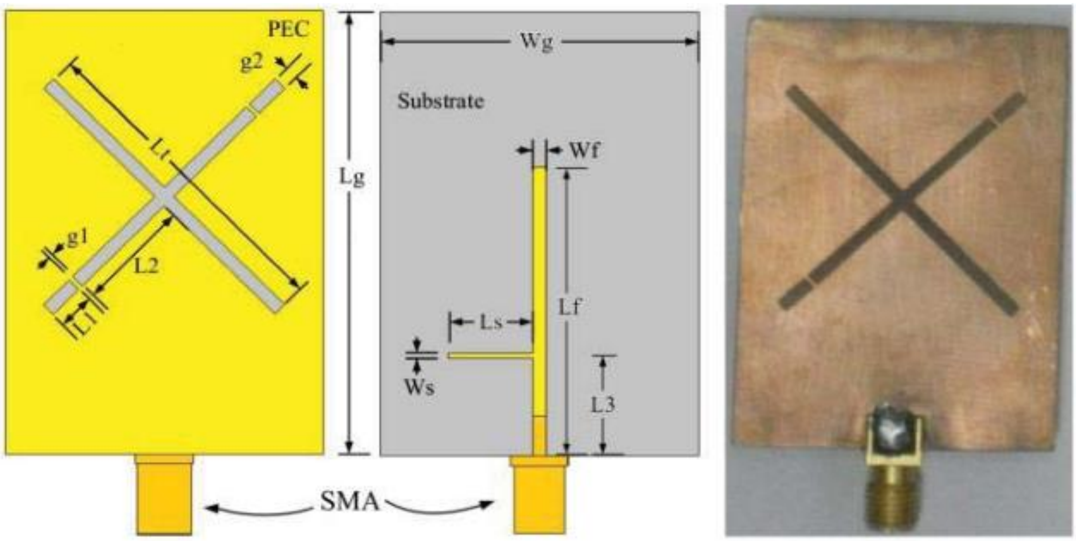


Figure 2.9. Crossed Slots [19]

2.3.3 Dual-fed patch antenna

A dual-fed patch antenna can be designed to produce circular polarization. This involves feeding the patch element with two orthogonal modes at a specific phase difference to produce circular polarization. The two modes can be fed using two different feeds or a single feed with a hybrid coupler [18].It offers several advantages over single-fed patch antennas, such as improved impedance matching, increased bandwidth, and the ability to generate various radiation patterns. This technique is illustrated by figure 2.10.

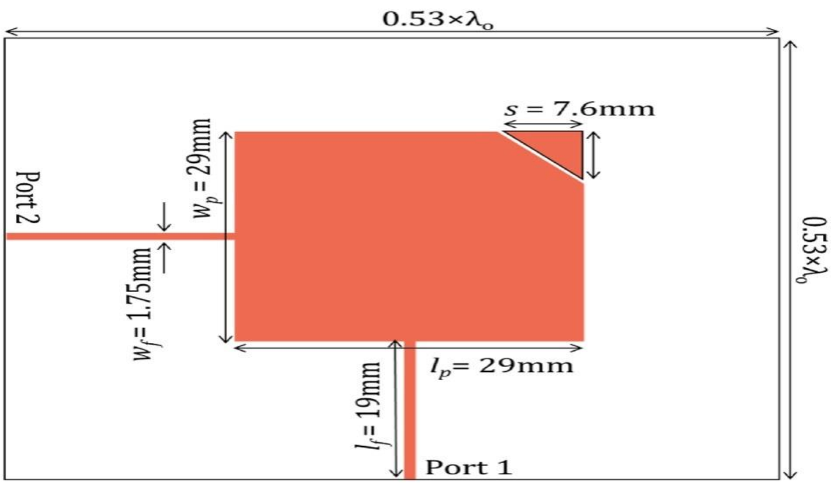


Figure 2.10. Dual-Fed Patch Antenna [18]

2.3.4 Cavity-backed patch antenna

A cavity-backed patch antenna can be designed to produce circular polarization. This involves adding a metallic cavity behind the patch element to improve the radiation pattern and produce circular polarization [19]. The cavity structure improves the antenna's radiation efficiency, reduces back radiation, and provides better impedance matching. It results in a directional radiation pattern with higher gain and wider bandwidth compared to conventional micro-strip patch antennas.

Cavity-backed patch antennas are used in applications requiring high gain, directional radiation, and good impedance matching, such as satellite communication, radar systems, and wireless networks. An example of cavity patch is illustrated by figure 2.11.

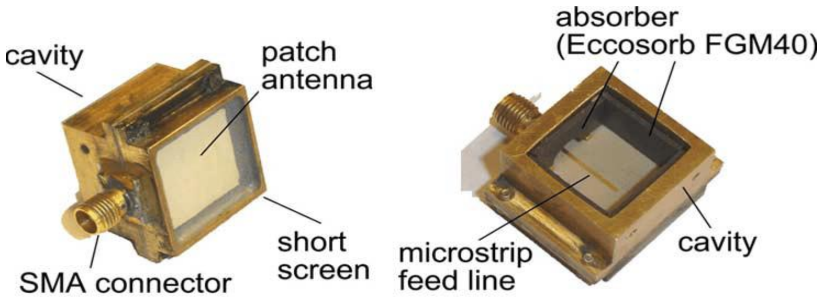


Figure 2.11. Cavity-Backed Patch Antenna [19]

2.3.5 Slotted patch

A slotted patch refers to a type of antenna design commonly used in wireless communication systems, especially in microwave and millimetre-wave frequencies. It consists of a rectangular or circular conductive patch with one or more slots cut into it.

The slots in a slotted patch antenna serve to modify the radiation pattern and characteristics of the antenna. They can be used to achieve specific beam shapes, improve antenna efficiency, reduce side lobes, or create polarization diversity. By adjusting the shape, size, and arrangement of the slots, engineers can tailor the antenna's performance to meet the desired requirements [20]. There is several of slots shapes and figure 2.12 illustrate one of this shapes.

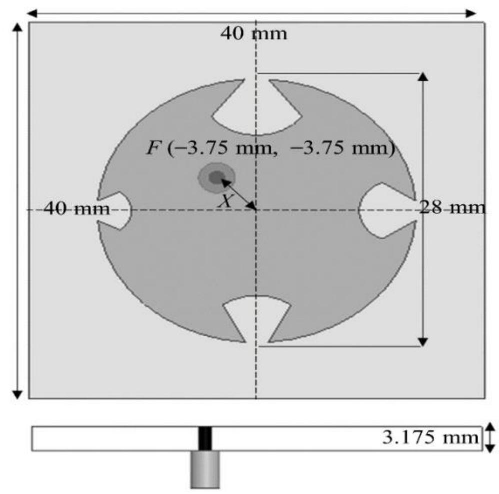


Figure 2.12. Example of slotted patch antenna [20]

2.3.6 Trimmed square

The trimmed square patch antenna is highly favoured in wireless communication applications due to its compact size, low profile, and ease of fabrication. It comprises a square metallic patch placed on a dielectric substrate, where the corners are trimmed to enhance its radiation characteristics. The antenna is fed through a micro-strip line or coaxial cable, usually located at the centre or an off-centre position on one side of the square patch. The resonant frequency is determined by various factors such as the square's side length, substrate thickness, and dielectric constant of the material used. The radiation pattern exhibits a primary lobe perpendicular to the patch plane, and adjusting the antenna's dimensions and feed position can further shape and optimize this pattern [20].

The trimmed square patch antenna can be designed for linear or circular polarization, depending on the feeding mechanism and patch geometry. This technique is illustrated by figure 2.13.

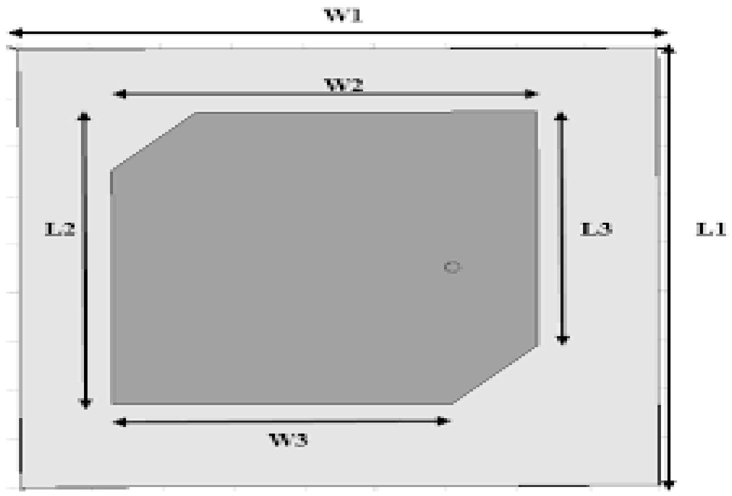


Figure 2.13. Trimmed square patch antenna [20]

2.3.7 Meta-surfaces

Meta-surfaces are two-dimensional structures composed of sub wavelength-sized elements arranged in a periodic or periodic pattern. They are engineered surfaces that can manipulate and control the behaviour of light, sound, or other types of waves in unprecedented ways. Meta-surfaces enable precise control over the phase, amplitude, polarization, and direction of wave propagation.

The sub wavelength elements, also known as meta-atoms, are typically designed to exhibit specific electromagnetic properties at the desired frequency range. These meta-atoms can be metallic, dielectric, or a combination of both, depending on the intended functionality of the meta-surface. By carefully designing the shape, size, and arrangement of these meta-atoms, the meta-surface can manipulate incoming waves with exceptional control [21].

Meta-surfaces can be utilized for circular polarization control in various applications. Circular polarization refers to the polarization state of electromagnetic waves in which the electric field vector rotates in a circular manner as the wave propagates. Meta-surfaces can manipulate the polarization of incident light to generate, convert, or control circular polarization. An example of Meta-surfaces technique is illustrated by figure 2.14

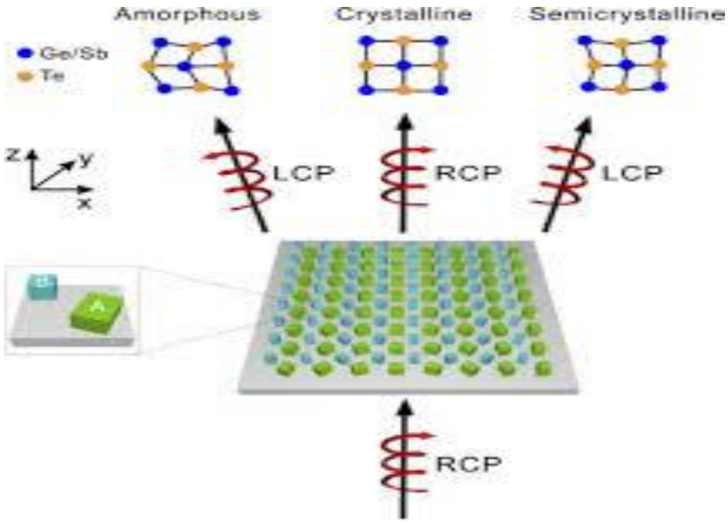
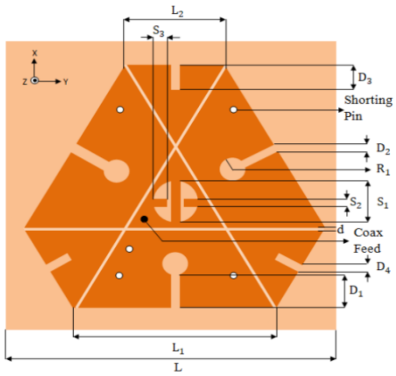
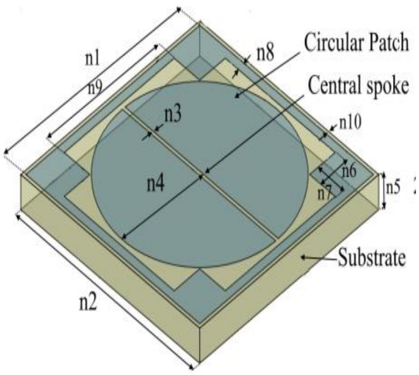


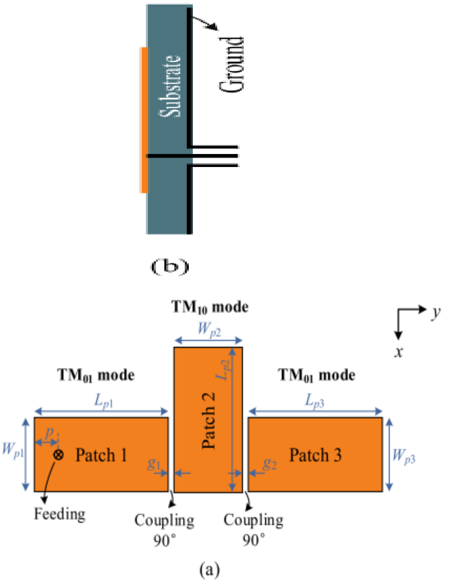
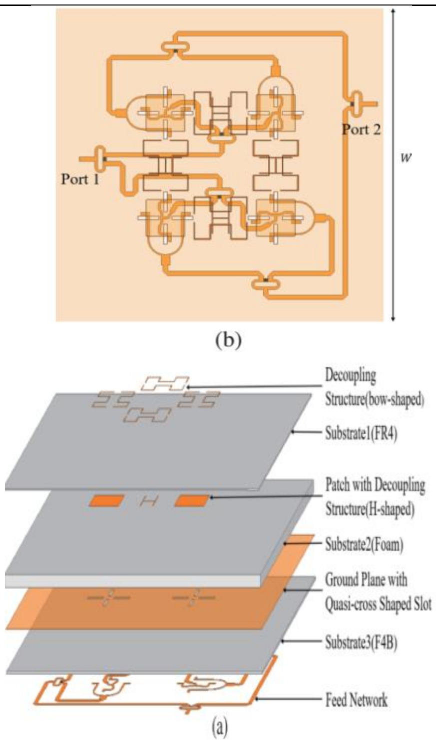
Figure 2.14. Meta-surfaces technique [21]

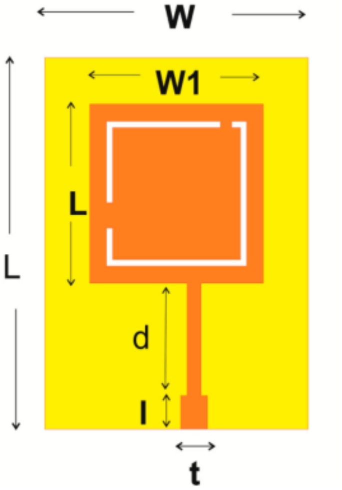
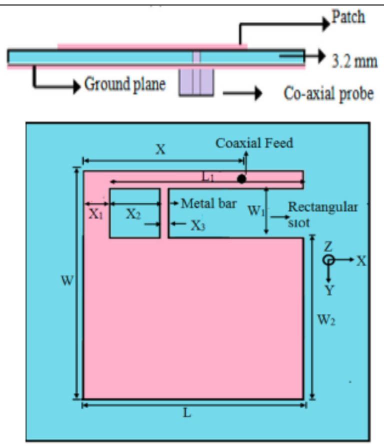
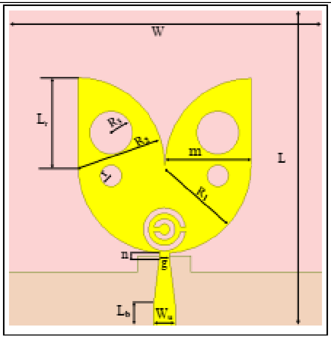
2.4 Scientific review

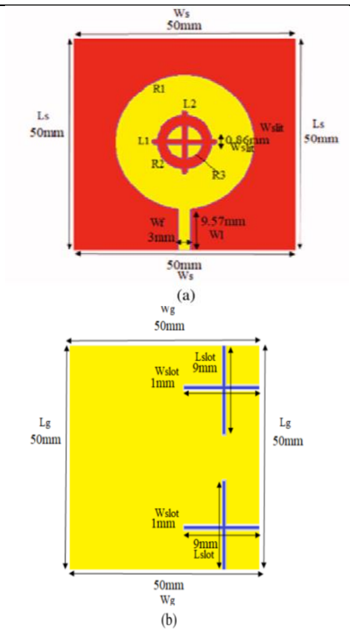
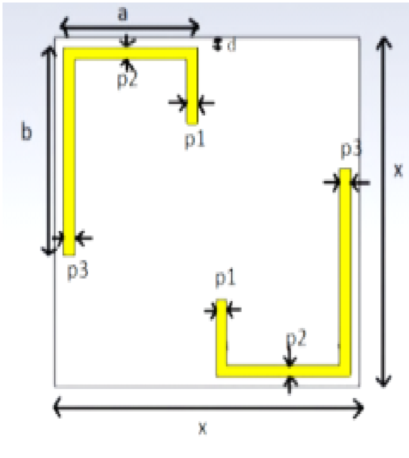
The following table represents a non-exhaustive scientific review of multiband circularly polarized antennas:

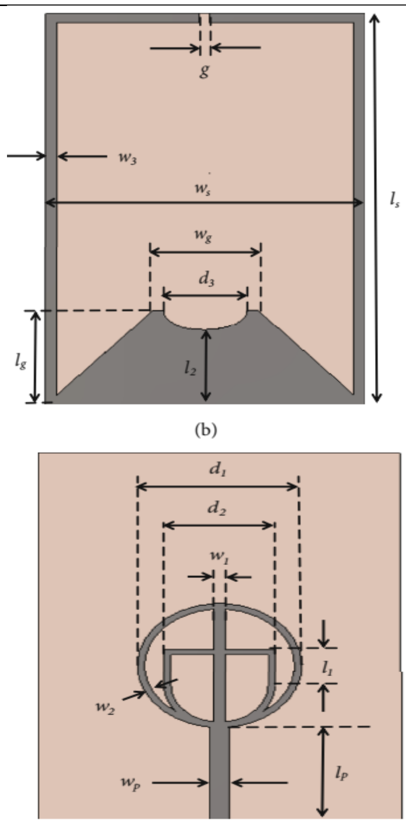
Table 2.1A scientific review of multiband circularly polarized antennas.

References	Geometry	Size	Frequency
[22]		**55 mm x 55 mm x 3.2 mm**	**L5 (1176.45 MHz) and L1 (1575.42 MHz)**
[23]		**0.13λ2.97 GHz × 0.13λ2.97 GHz**	**2.97 GHz and 7.77 GHz in y-direction. 3.14 GHz and 10.90 GHz in the x-direction.**

[24]		0.59×0.59×0.15	3.35 to 3.59 GHz- 3.42 to 3.61 GHz
[25]		120 mm x 120 mm x 5.4 mm	4.6-6.5 GHz for left-hand circular polarization (LHCP). 4.86-6.5 GHz for right-hand circular polarization (RHCP).

[26]		**40 mm× 29 mm × 1.6 mm**	**3.35 to 3.9 GHz and 4.8 to 6 GHz**
[27]		**50 mm× 50 mm × 3.2 mm**	**5.76–7.35 GHz and 7.6–8.79 GHz**
[28]		**30 mm x 30 mm x 1.65 mm**	**4.40 - 7.71 GHz and 8.42 – 13.24 GHz**

[29]	 . (a) Front view and (b) back view.	**50 mm × 50 mm × 0.16 mm**	**6.2 GHz, 7.8 GHz, and 9.3 GHz**
[30]		**7.95mm×7.95mm ×3.1mm**	**6.75GHz-12GHz 9GHz-14.0GHz**

[31]	(a) (a) Front and (b) back view	**20 mm× 15mm × 0,5 mm**	**3.2-10.5GHz 10-15GHz**

This scientific review centres on multiband circularly polarized patch antennas, emphasizing that the majority of these antennas are currently dual-band and lack the desired compactness. Despite their advantages for wireless communication, these antennas often exceed the preferred compact form factor. The review underscores the importance of further research to enhance their compactness and address the need for triband capability. Achieving both multiband operation and compactness is crucial for integrating these antennas into modern communication devices.

2.5 Conclusion

In summary, this chapter discussed multiband and circular polarization techniques in antenna design. Various approaches were explored to achieve multiband operation, including resonant structures, parasitic elements, and tuneable components. Circular polarization techniques, such as crossed dipoles and helical antennas, were also examined for their benefits in signal reception. The chapter is concluded with a bibliographic synthesis, providing a valuable collection of research works in these areas. Overall, these techniques contribute to the advancement of antenna design and cater to the evolving needs of wireless communication systems.

Chapter 3: Design and Simulation of tri-band CP antenna.

3.1 Introduction

In this chapter, the complexity of the design and electromagnetic simulation of a circularly polarized triple band patch antenna are analysed. The specifications for this work were meticulously outlined, with the ultimate objective being the creation of a circularly polarized antenna that could effectively operate within three distinct frequency bands, as radio-navigation GPS 1.575 GHz, ISM 0.902 GHz and ISM 2.4 GHz.

Following this, a detailed methodology and step-by-step study of the results are represented, detailing each technique employed and interpreting the results obtained until meeting all the specifications. Finally, we provide a comparative analysis of the antenna developed in this work with other references to highlight its distinct advantages.

3.2 Technical specifications

In this project, the designed printed antenna should fulfil the technical specifications summarized in table 3.1.

Table 3.1: Specifications table.

Parameters	Specifications
Operating bands	ISM [0.902]GHz GPS [1.575]GHz ISM [2.4] GHz
Size	As compact as possible
Gain	Positive
AR beam-width	180°
AR bandwidth	<3dB
Reflection coefficient	|S11|<-10 dB

3.3 Methodology and simulation

To accomplish our objective of designing a triple band circularly polarized antenna, we employ a designated set of procedures known as methodology, which will be explored in the following sections.

3.3.1 Dual pin feed access antenna for circular polarization

To acquire circular polarization, we used a widely employed method known as the dual access port simultaneously excited with equal amplitude wherein the phase disparity between the two ports is set at 90 degrees [32].This method was implemented on a basic square patch antenna, as visually depicted in figure 3.1. The square patch printed on separate FR4 substrates (relative permittivity of ε=4.4) and a loss tangent of 0.02 with a thickness of 3.2mm, this patch has been exported from antenna magus.

The structural configuration of this antenna was specifically exported to operate in the central frequency of [1.6] GHz, where the impedance matching attains a level lower than -10 dB and the axial ratio remains below 3 dB.

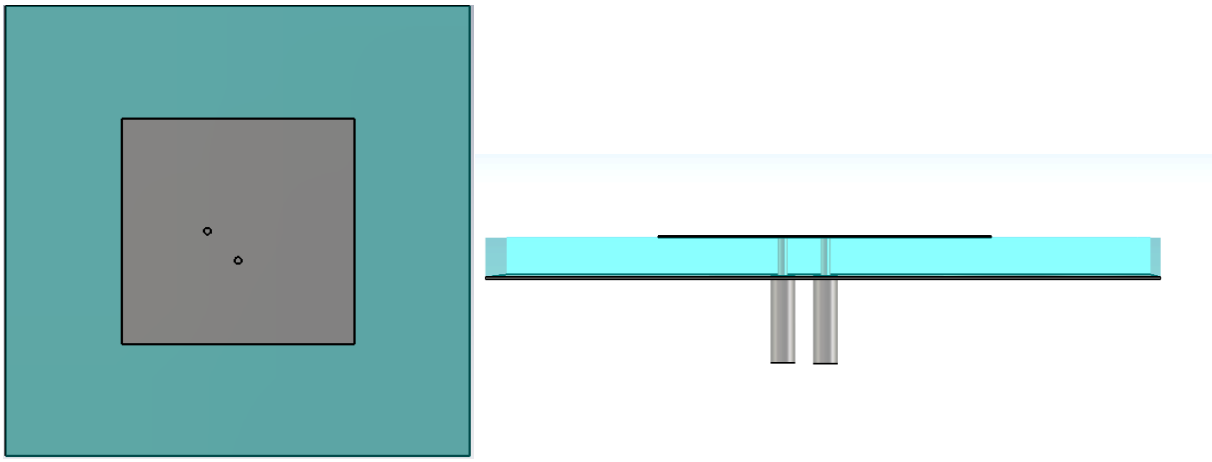


Figure 3.1.A mono band CP patch antenna with dual pin feed access.

Simulation results are shown in figure 3.2 for reflection coefficient and 3.3 for axial ratio.

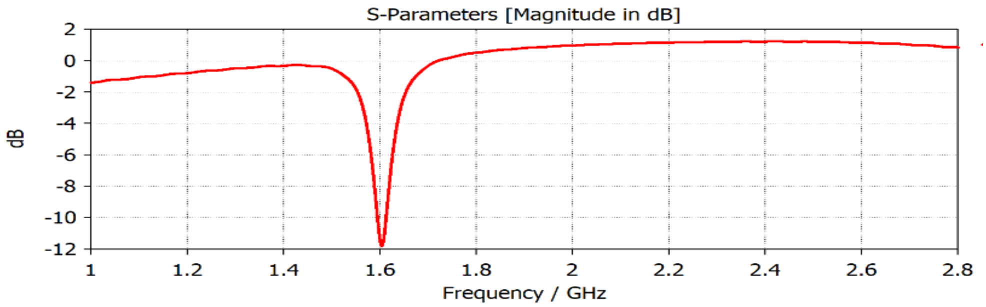


Figure 3.2. S11 of dual pin feed access antenna.

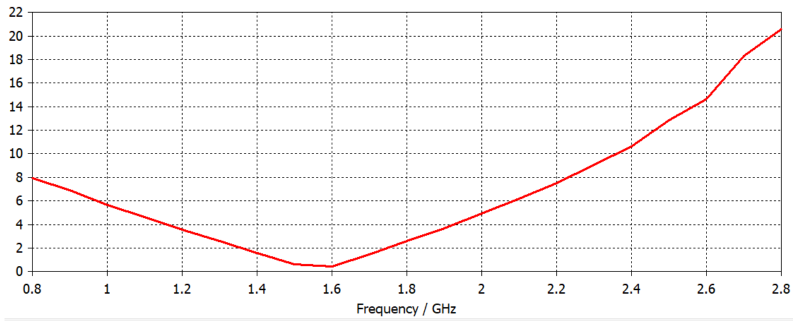


Figure 3.3. AR bandwidth of dual pin feed antenna.

Based on the obtained simulated results, it becomes evident that a single frequency band at 1.6 GHz and an axial ratio (AR) are achieved. Nonetheless, the range of AR in terms of band width is excessively narrow to be considered acceptable. Hence, this observation justifies the need for the next step.

3.3.2 Four pin feed access antenna for circular polarization

To enhance the performance of the axial ratio, we implemented an additional technique related to the initial approach; however, this time it entailed incorporating four feeding accesses instead of two. The representation of this design can be observed in figure 3.4

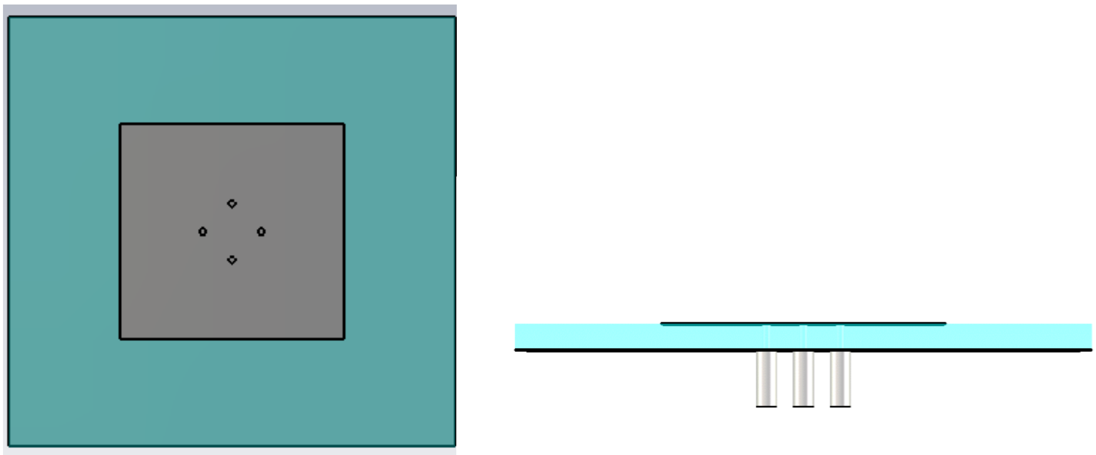


Figure 3.4. Four pin feed access antenna.

Simulation results are shown in figure 3.5 for reflection coefficient and 3.6 for axial ratio.

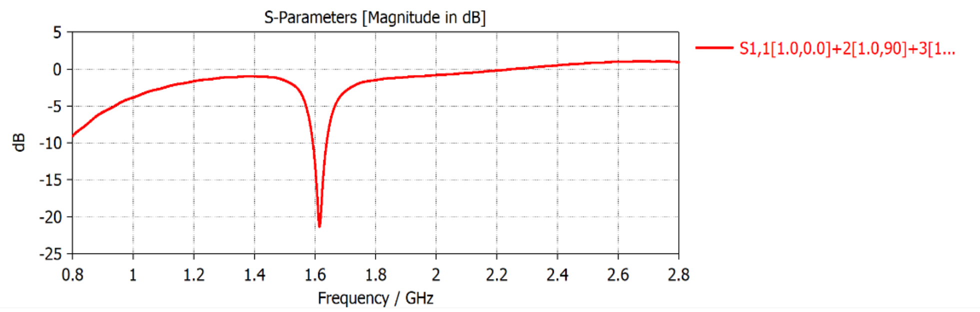


Figure 3.5. S11 of four pin feed access antenna.

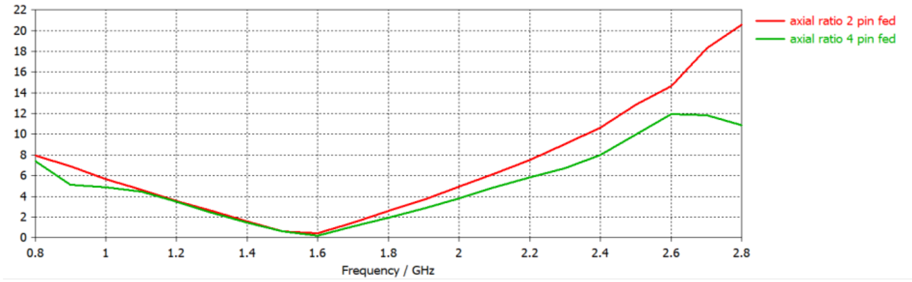


Figure 3.6.AR of two and four pin feed access antenna.

The derived outcomes illustrate a notable enhancement in the performance of the AR, accompanied by the added advantage of improved matching results. Consequently, we can assert that this design will serve as the base upon which the next work will be built.

Where:

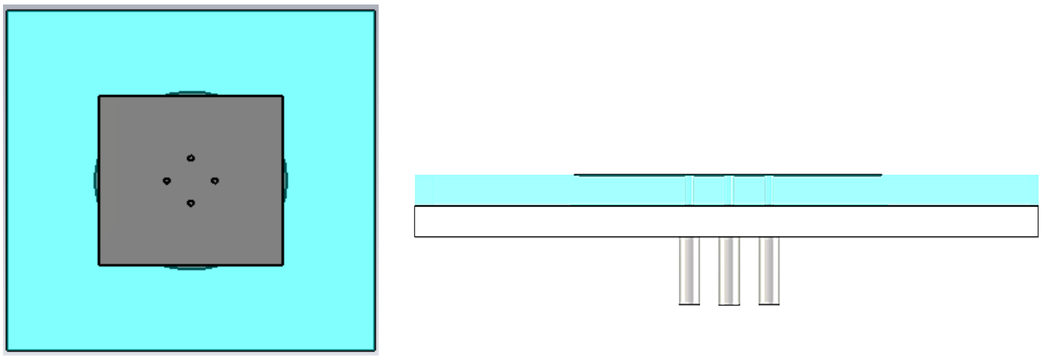
The S11: is the reflexion coefficient.

The AR: is the axial ratio is defined as the ratio of the major axis to the minor axis of the polarization.

3.3.3 Stacked technique for triple band

Upon successful attainment of circular polarization (CP), the subsequent objective at hand is to accomplish triple band. Among the widely employed techniques to achieve this goal is the use of a stacked patch antenna, which is implemented during this phase. As the figure 3.7 shows, the direct connection between the probe feed and the upper patch is established, while the lower patch is fed indirectly through a small clearance hole that separates the probe from the patch. For the bottom patch, the substrate utilized is Rogers RT5880, (with a thickness of 3.2 mm and relative permittivity of 2.2).

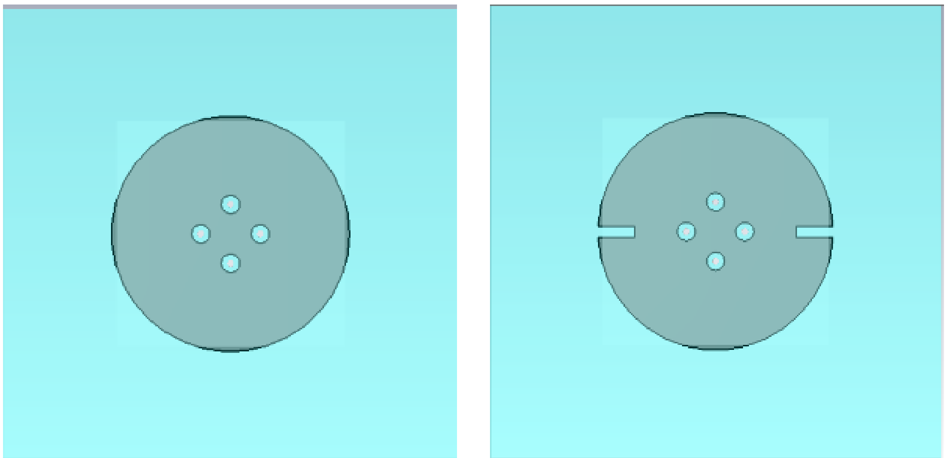
In the initial attempt, we employed a circular patch as the lower component with four clearance holes, as visually depicted in figure 3.8. However, in the subsequent iteration, we replaced the circular bottom patch with a square counterpart, with a specific emphasis on manipulating the dimensions of our structure to approach our desired specifications. A visual representation is provided in figure 3.9



(a) (b)

Figure 3.7. Stacked patch antenna, (a) front view , (b) side view.

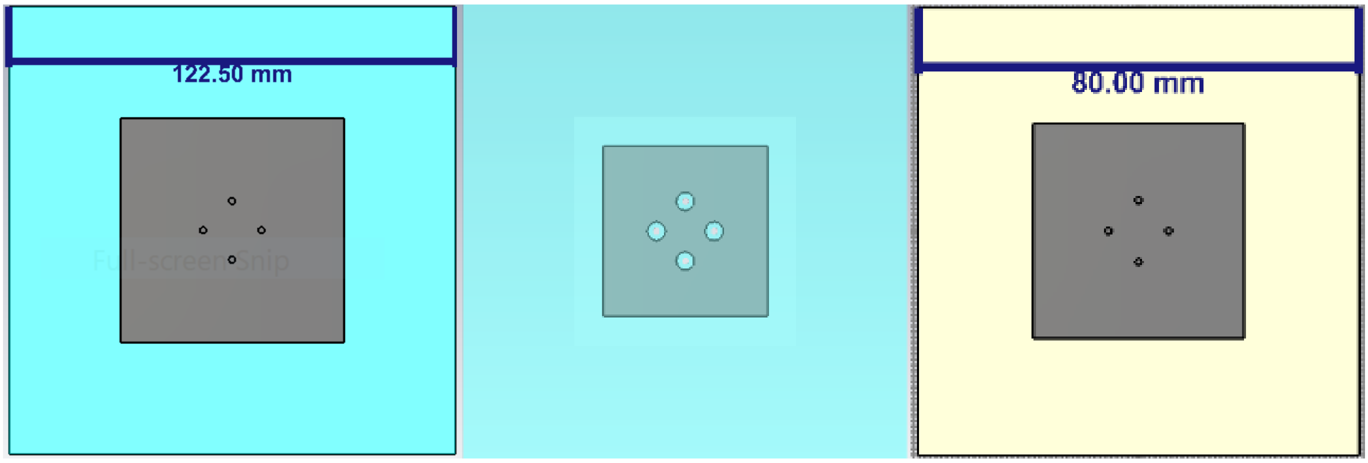
a. stacked patch with circular patch in the bottom



(a) (b)

Figure 3.8. Stacked technique where the bottom is circular patch, (a) bottom patch , (b) bottom patch with slots.

b. stacked patch with square patch in the bottom



(a) (b) (c)

Figure 3.9. Stacked technique where the bottom is square, (a) front view for 122 mm, (b) bottom view, (c) front view for 80 mm.

The simulation results are represented in figure 3.10

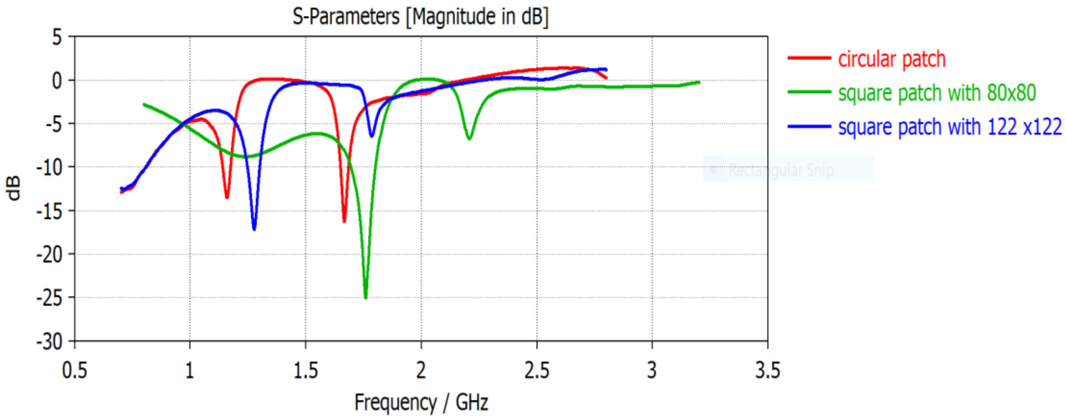


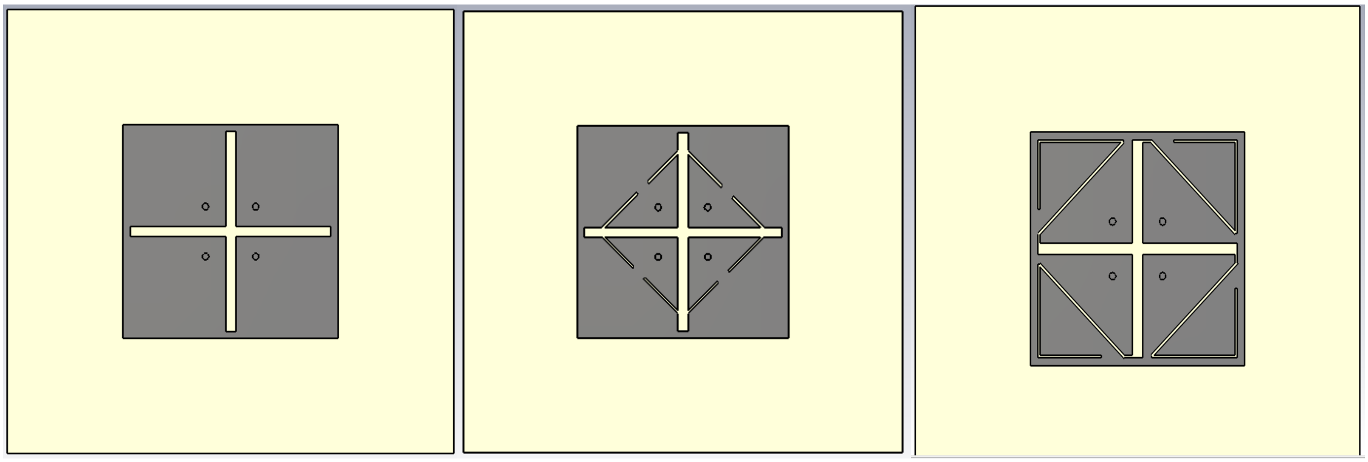
Figure 3.10.S11 comparison of different bottom patch.

In Figure 3.10, the red curve denotes the S11 characteristic of the lower circular patch, whereas the blue and green curve represent the S11 behaviour of the square bottom patch, differing in their dimensions of 122 x 122 $mm^2$and 80 x 80 mm^2 respectively.

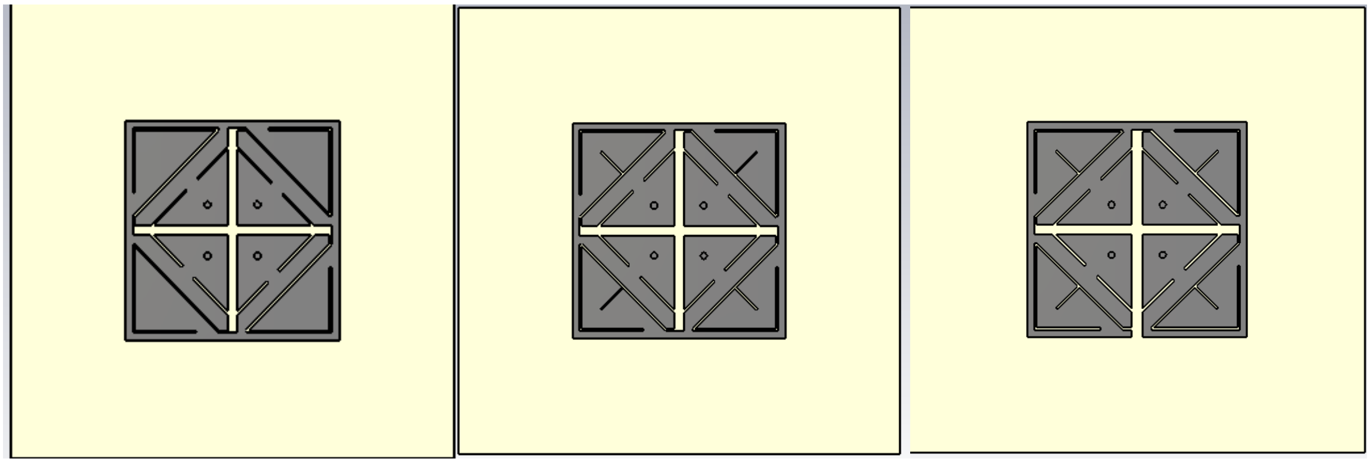
The aforementioned results reveal that the circular patch exhibits undesired resonance within a dual frequency range. This circumstance prompted us to consider the utilization of a square patch. The initial patch, sized 122 x 122 mm^2, slightly shifted the frequency range but still fell short of meeting the required specifications. However, the patch measuring 80 x 80 mm^2 approximated the desired outcomes, albeit with a narrower frequency band .The exclusive acquisition of circular polarization has been accomplished within a solitary frequency band. It is evident that the implementation of the stacked patch antenna technique alone does not suffice to accomplish our objective, thereby warranting the justification for the subsequent step.

3.3.4 Upper patch configuration

To enhance the performance of the S parameters, we find ourselves compelled to introduce a combination of a cross slot technique and an array of slots. These slots serve as symbolic manifestations of the degrees of freedom required to establish interconnections among the disparate sections of the upper patch antenna. This complex arrangement is visually represented in figure 3.11.

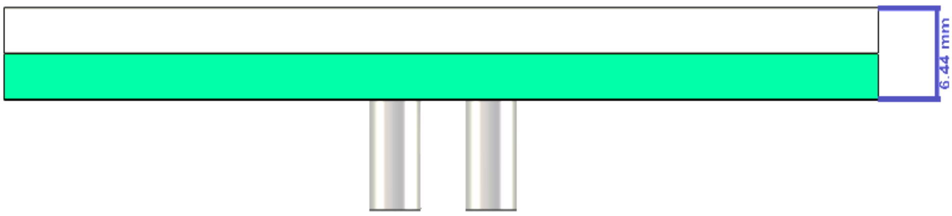


Step 1 step 2 step 3



Step 4 step 5 step 6

(a)



(b)

Figure 3.11. The design of the upper patch with 6.44mmthickness, (a) the different steps for the upper patch configuration, (b) side view.

The simulation results are visually represented in figure 3.14.

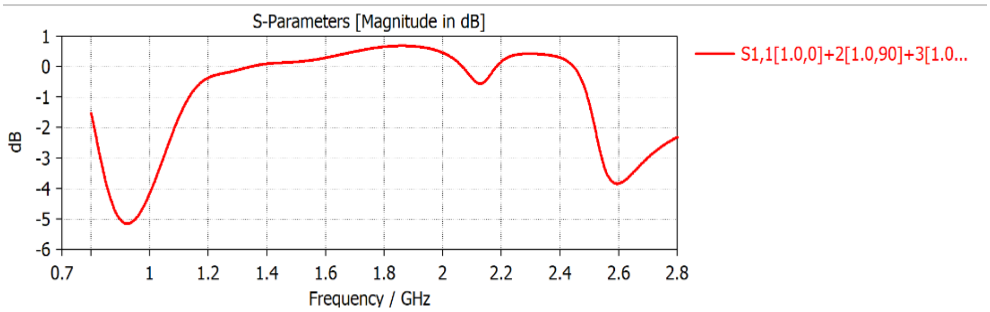
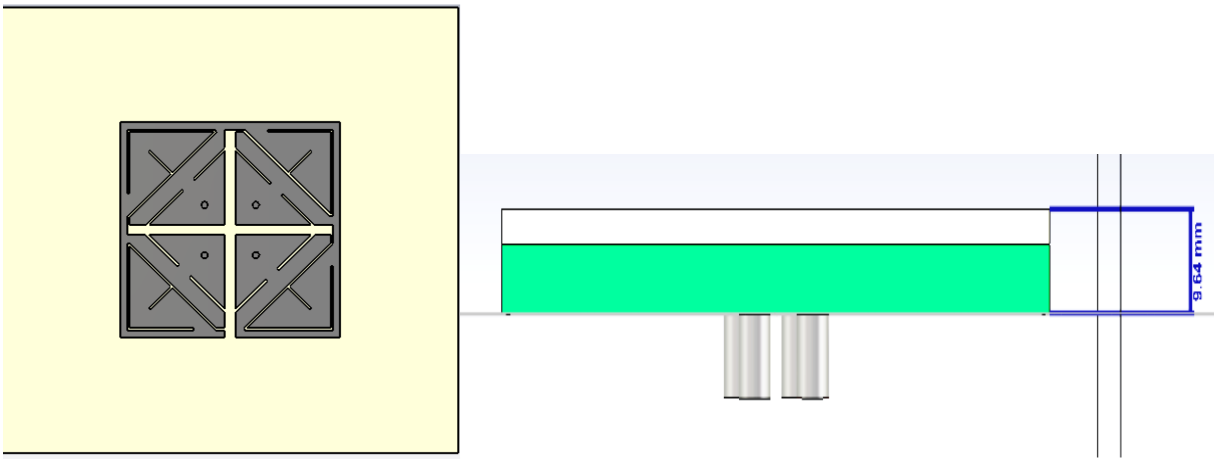


Figure 3.12.S11 of the upper design with 6.44 mm thickness.

As expected, notable enhancements were observed in the performance of the S parameters. The desired dual-band (ISM) behaviour was achieved, albeit with the exception of the matching characteristic failing to reach the desired threshold of -10 dB in the S11 parameter, and notable absence for the GPS band.

By attaining an approximation to the specified requirements, it stimulated contemplation regarding the configuration of an additional parameter. This subsequent step, as illustrated in figure 3.13, will shed light on the proposed configuration.



Front view side view

Figure 3.13. The final design of the upper patch with 9.64 mm thickness.

Figure 3.14 represents the simulation results of the antenna depicted by figure 3.13

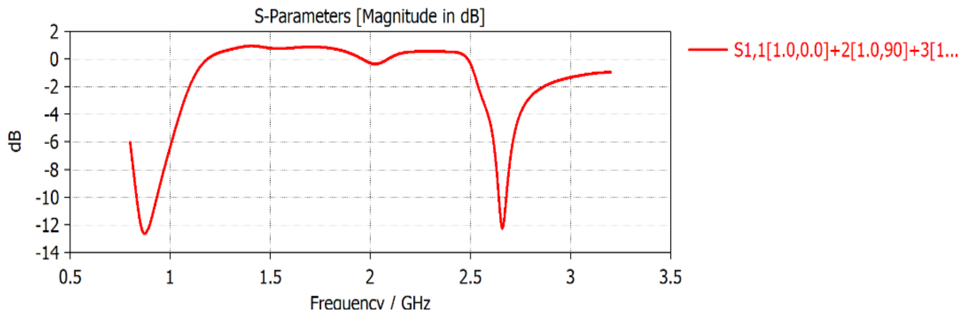


Figure 3.14.S11 of the upper patch with 9.64 mm thickness.

Through the incorporation of multiple layers within the substrate thickness, notable enhancements were observed in the S11 parameters, as it is shown in Figure 3.14. The desired dual-band (ISM) behaviour has indeed been attained, albeit with the consideration that the frequency range does not precisely align with the intended specifications and an absence of the GPS band.

At this point, it is safe to assert that the configuration of the upper patch antenna has reached its culmination. Subsequent efforts will be directed towards the configuration of the bottom patch antenna.

Upon conducting a concise parametric analysis pertaining to the substrate, it is apparent that superior outcomes are obtained with a thickness of 6.4 mm in the bottom substrate. Consequently, all subsequent efforts will be based on this particular thickness.

3.3.5 The bottom patch optimization

a. Annular ring technique

In our pursuit to align the frequency range with the prescribed specifications, we resorted to the utilization of a widely recognized technique within the field: the implementation of an annular ring slot on a square patch antenna, as illustrated in Figure 3.15.

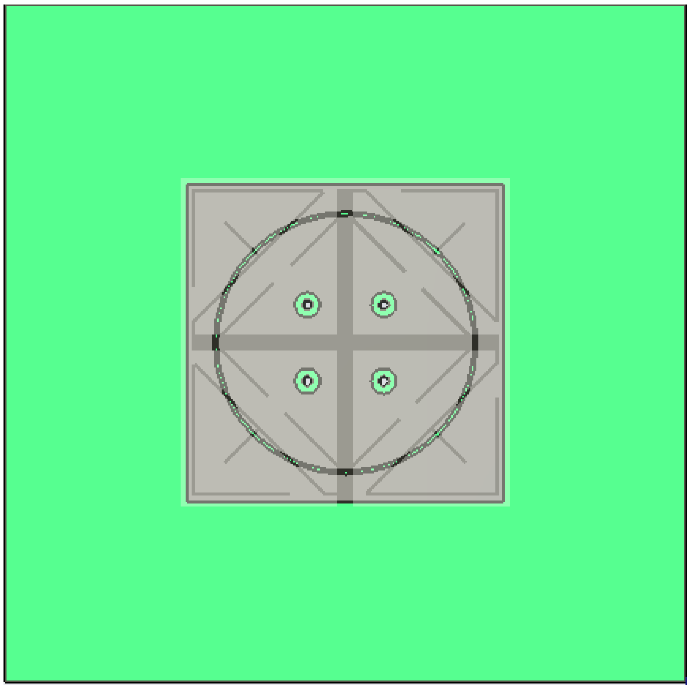


Figure 3.15. Annular ring technique.

Figure 3.16 shows the S11 of the annular ring technique.

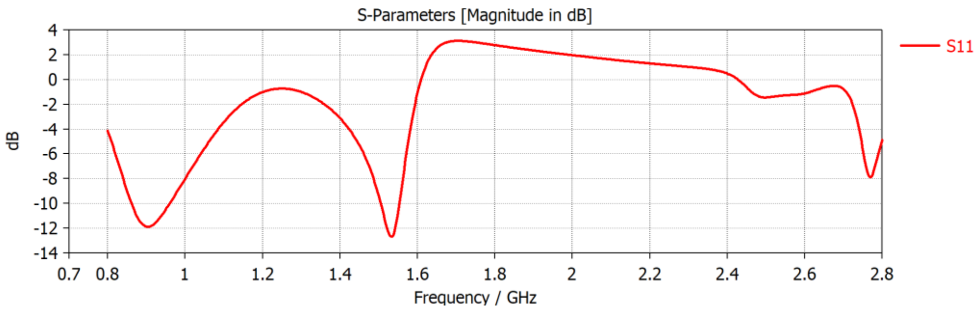


Figure 3.16.S11 of the annular ring technique.

Figure 3.17 shows the AR beam-width results

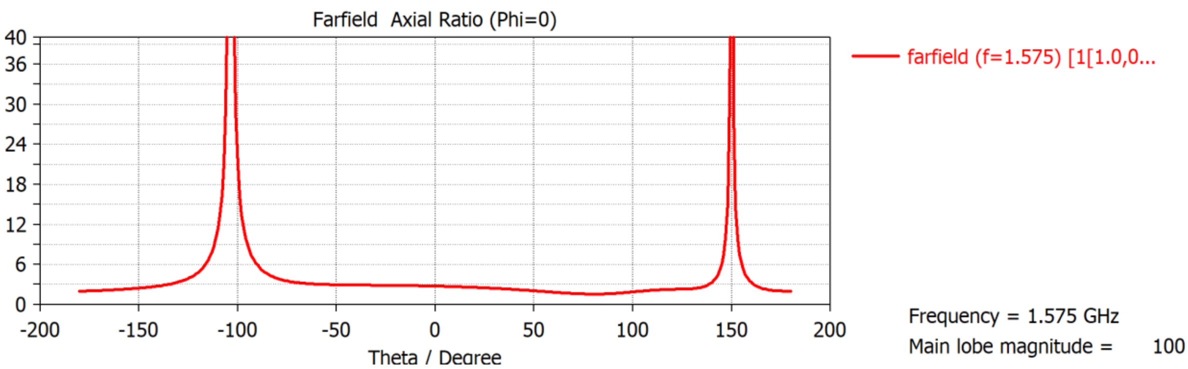


Figure 3.17. AR results of the annular ring technique.

Upon careful examination, it becomes evident that a tripleband has been attained, albeit with only two frequency range conforming to the specified requirements [1.5-1.6] GHz and ISM lower band [902 MHz] Regrettably, the third frequency range falls outside the desired specifications, due to the absence of interconnection within the bottom patch. Additionally, the AR results were not good enough, so we couldn't achieve the desired CP either.Consequently, the subsequent phase of our work is dedicated to the rectification of this predicament.

b. annular ring optimization

In an effort to address the deficiency caused by the absence of interconnections, we implemented an augmentation to the patch structure in the form of four tabs. This modification is illustrated in Figure 3.18.

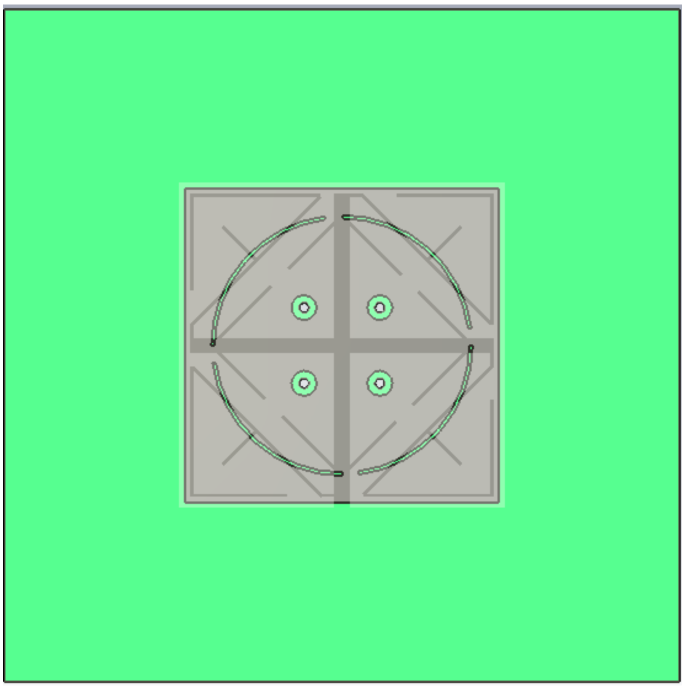


Figure 3.18. Annular ring optimization using tabs.

Figure 3.19 bellow represent the S11 of two different substrate thickness

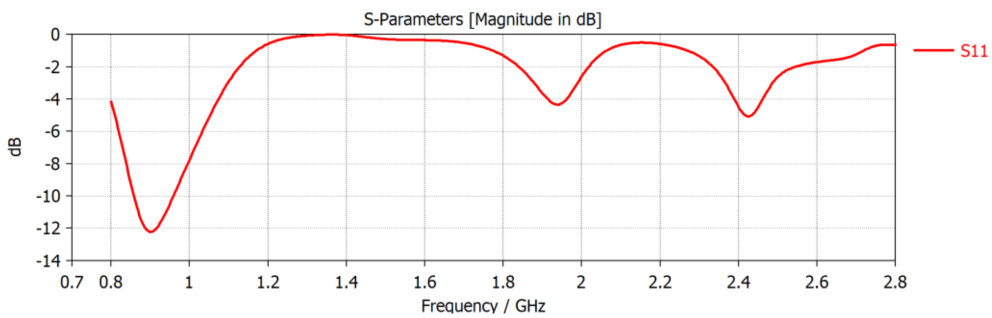


Figure 3.19. S11 of an annular ring with tabs.

As the results shows, we have made discernible progress towards achieving the desired results. Nevertheless, it is apparent that further modifications are necessary in order to attain improved impedance of matching. This signifies that we are on the precipice of the desired outcome, yet additional adjustments are warranted to optimize the overall performance.

c. annular ring optimization with slots

In accordance with the previous step, the introduced modifications encompass the inclusion of slots, as depicted in Figure 3.20 below. These slots serve as crucial elements in our ongoing pursuit of optimization.

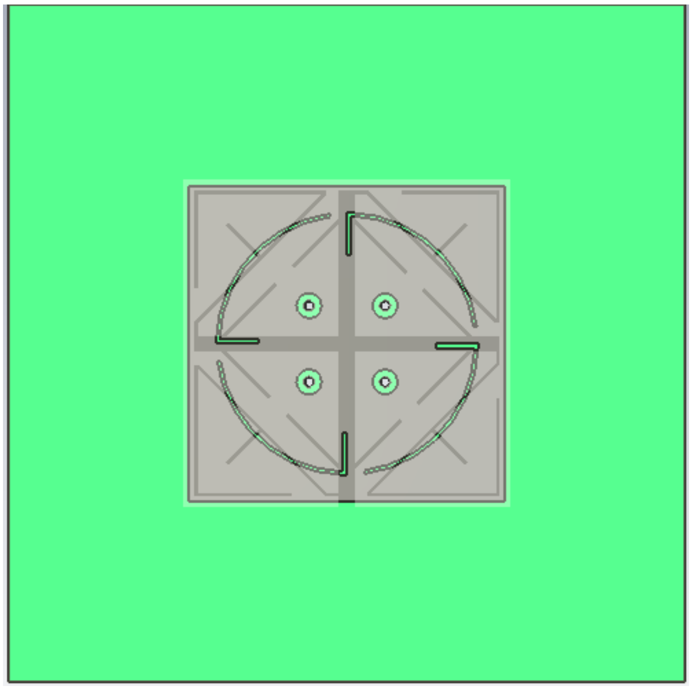


Figure 3.20. Annular ring optimization with slots.

The simulation results are shown in figure 3.21 for the S11 and figure 3.22 for the beam-width AR:

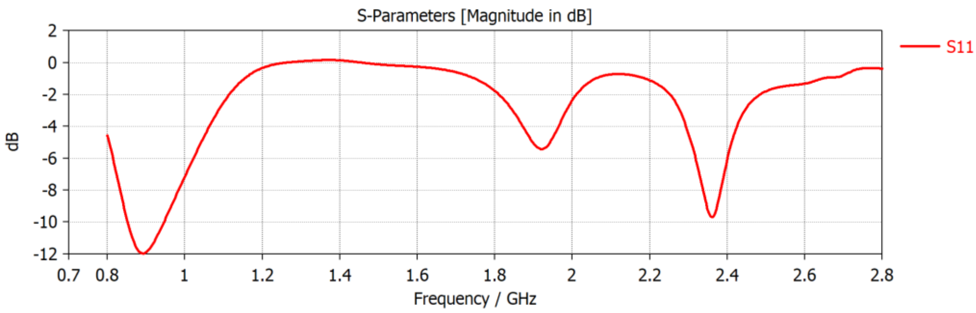


Figure 3.21.S11 annular ring optimization with slots.

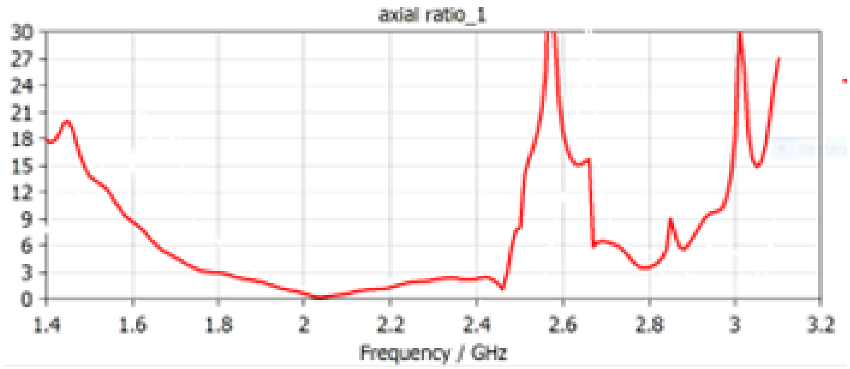


Figure 3.22.AR band -width annular ring optimization with slots in 2.4GHz.

The S11 representation in Figure 3.21 provides evidence that we are progressing along the correct trajectory towards achieving the desired dual band. Notably, we observe successful matching a both ISM band 2.4 GHz and 902 MHz However, the third frequency range displays a slight deviation and fails to reach the desired -10 dB threshold.

Consequently, we are compelled to employ an additional methodology to meet the prescribed specifications.

d. Dual annular ring technique

Upon successful acquisition of the ISM band, the subsequent task at hand involves securing the GPS band. This is accomplished by integrating the previously employed annular ring with a diminutive annular ring affixed to the four slots. This configuration is shown in figure 3.23.

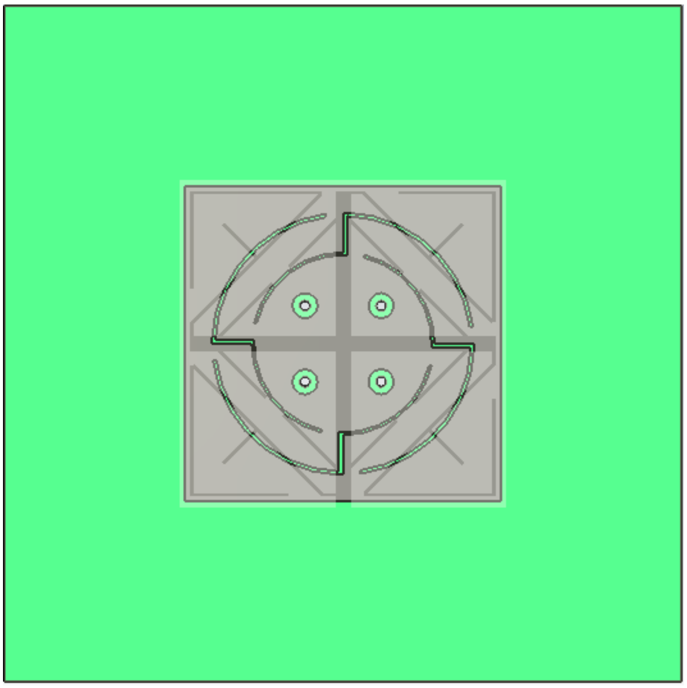
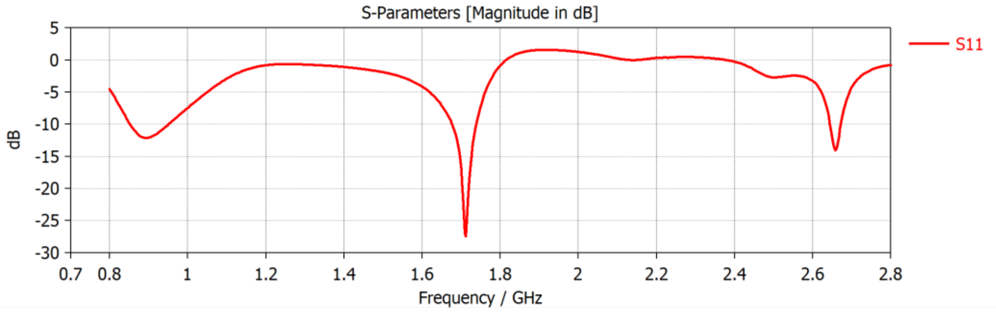
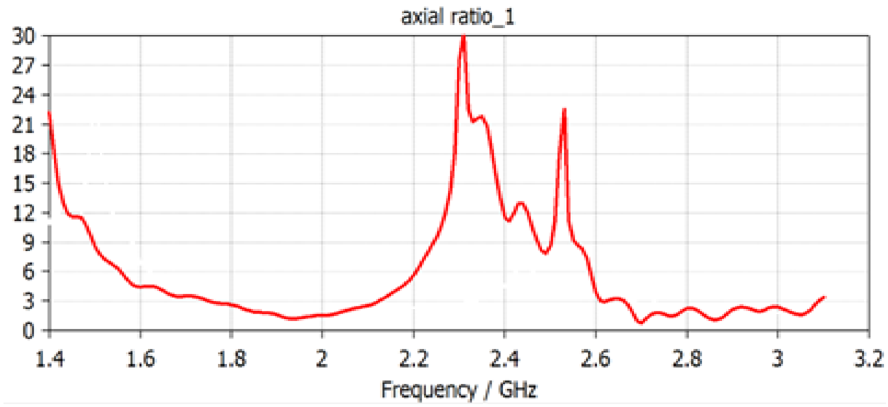


Figure 3.23. Dual annular ring technique.

The simulation results are shown in figure 3.24:



(a) S11



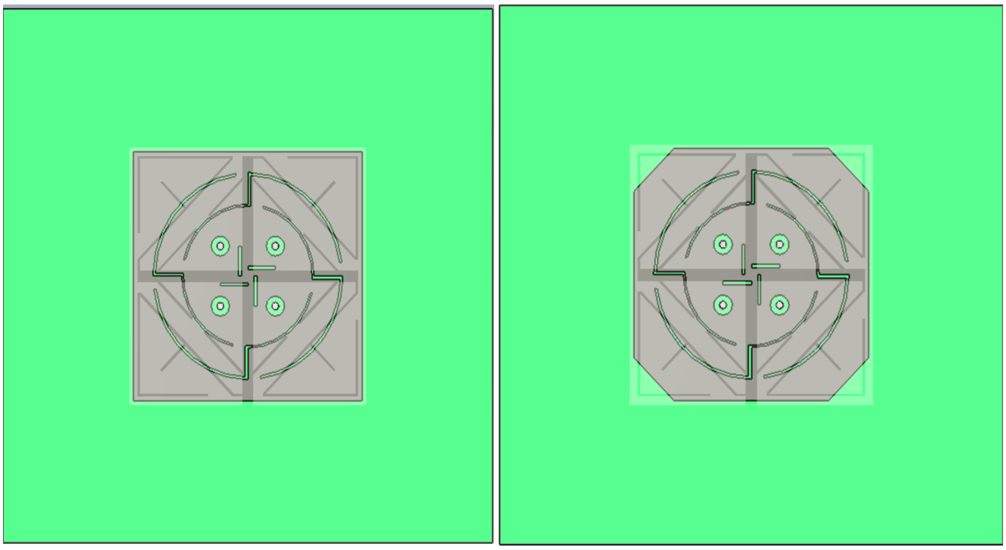
(b) Axial ratio vs. frequency

Figure 3.24. Simulation results of dual annular ring technique, (a) s11 (b) AR.

As demonstrated by these results, the desired frequency range has been nearly attained; however, there is a discernible shift in the ISM range. From this, we can infer that a triple band has been achieved, albeit without fully aligning with the specified requirements. Hence, further optimizations are still necessary for this antenna.

e. Final step in bottom patch optimization

In order to augment the performance of the lower patch antenna, we implemented a combination of commonly employed techniques. The initial approach involves the incorporation of centred slots, aimed at enhancing the circular polarization's freedom of movement and expanding the range of triple band operation. Subsequently, we utilized a technique known as "trimmed" to optimize the performance of the axial ratio (AR). A visual representation is in figure 3.25.



(a) (b)

Figure 3.25. The optimization of bottom patch by using (a) using centre slots, (b) using trimmed technique.

In pursuit of a more circular interconnection and an extended range for the axial ratio (AR) a series of slots have been strategically employed. The implementation and resulting effects of these slots can be observed in figure 3.26.

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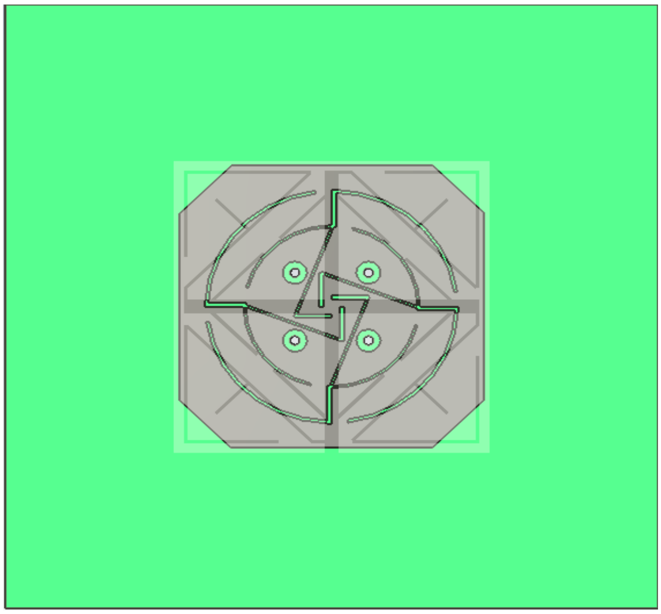


Figure 3.26. The final optimization in bottom patch.

The optimized results are shown in figure 3.27, where the pink one belonged to figure 3.25 and the red one to 3.26.

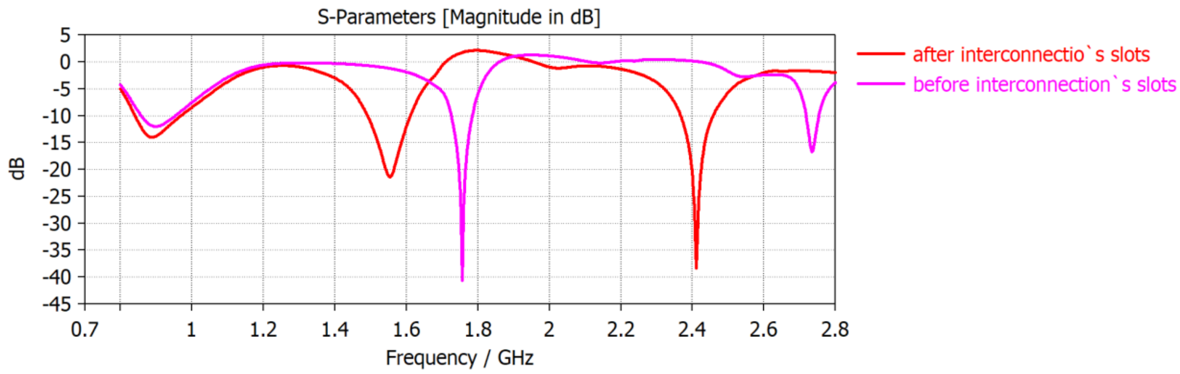
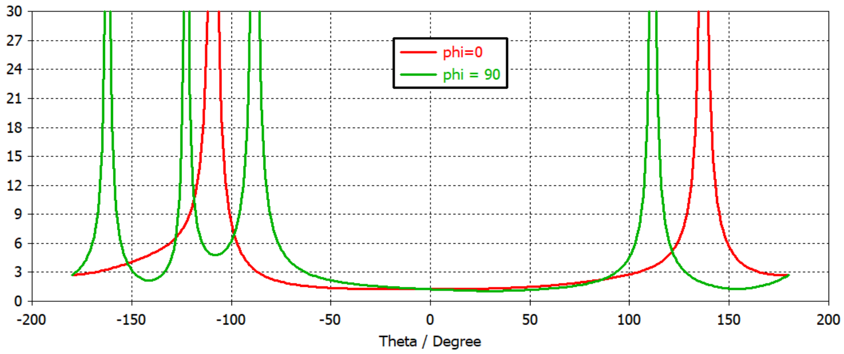
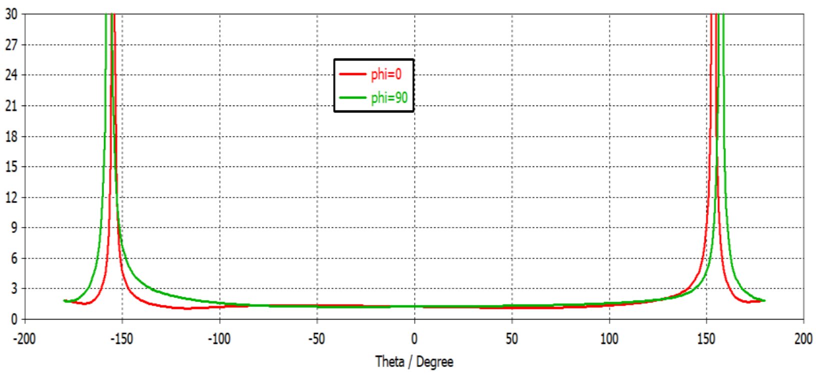


Figure 3.27. S11 of the Final optimization in bottom patch.

The AR beam-width results are shown in figure 3.28.



(a)



(b)

Figure 3.28. The maximum AR beam-width results, for both bands (a) 1,575 GHz, (b) for 2.4 GHz,

Through a comprehensive analysis of the acquired S11 parameter, it becomes apparent that the newly introduced slots necessitate interconnection, thereby requiring their integration with the existing structure of the annular ring and it is evident that the accomplishment of CP is observed in two out of three bands.

3.3.6 Final design and simulation results

In light of the derived outcomes, it can be affirmed that all the triple band functionality have been successfully attained, however the CP is only achieved in the GPS and the ISM higher band. As a result, this configuration represents the ultimate design solution, as figure 3.29 shows.

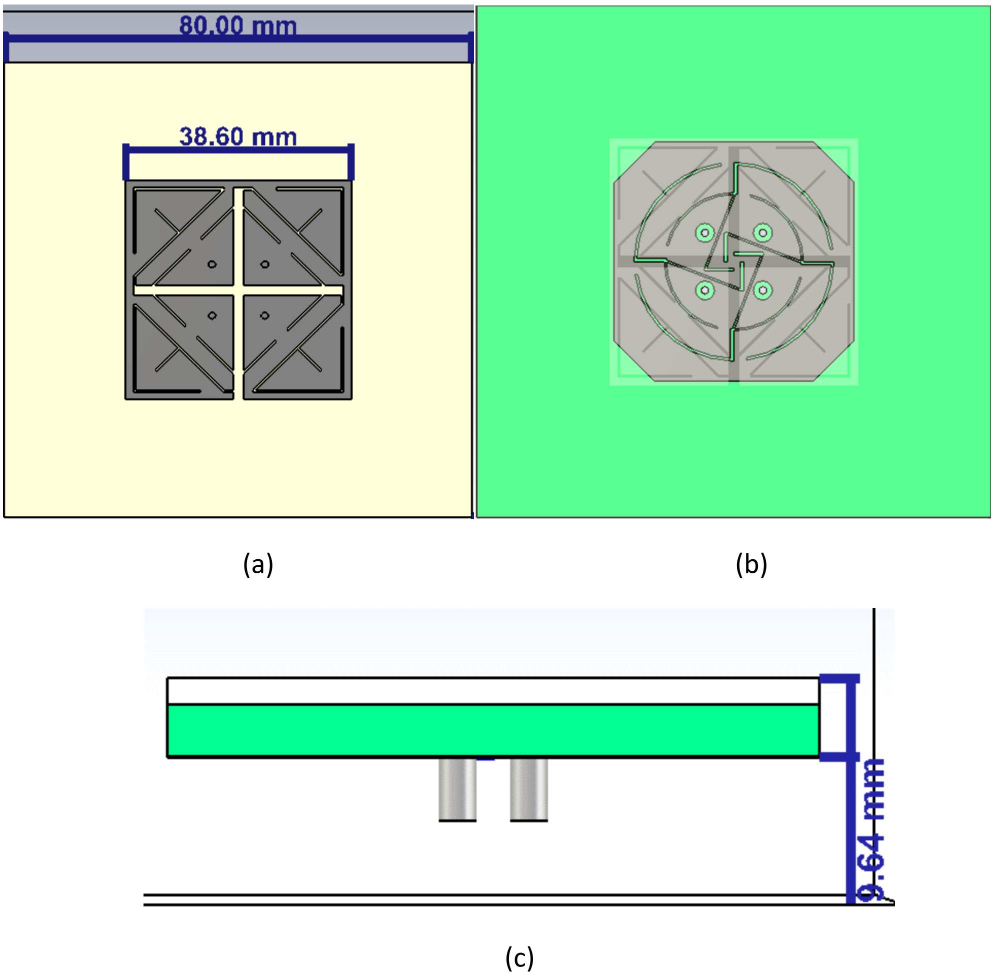


Figure 3.29. The final design of dual band circularly polarized antenna, (a) front view, (b) bottom view, (c) side view

The rest of the specifications will be discussed in the next part.

a. Reflection coefficient:

Figure 3.30 represents the S11 parameter obtained

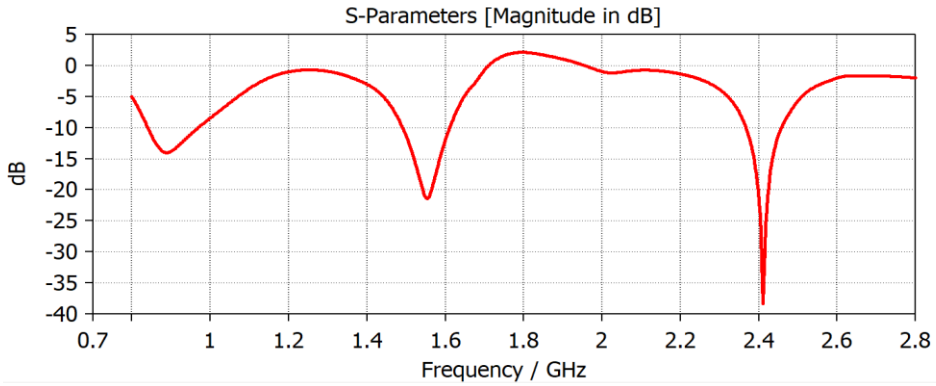


Figure 3.30.S11 of dual band circularly polarized antenna.

In light of the derived outcomes, it can be affirmed that all the triple band functionality have been successfully attained.

b. Axial ratio :

- **AR beam-width**

Figure 3.31, 3.32 and 3.33 shows the AR beam-width in different frequencies and both planes.

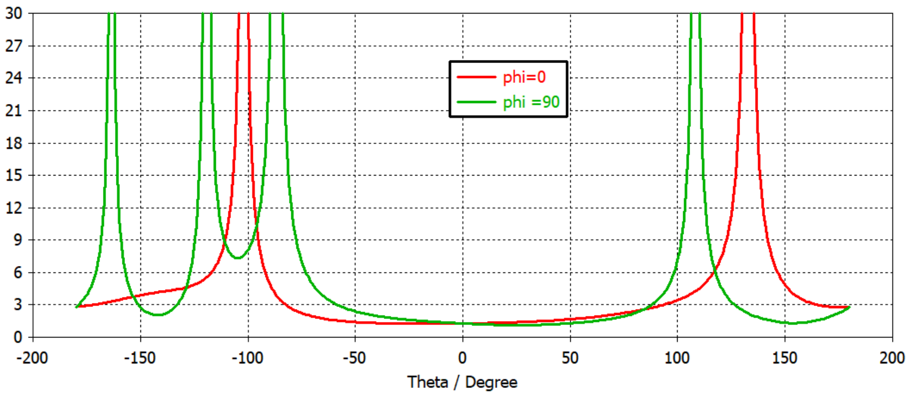


Figure 3.31. AR beam width for 1.575 GHz, (a) for Phi = 0°, (b) for Phi = 90°.

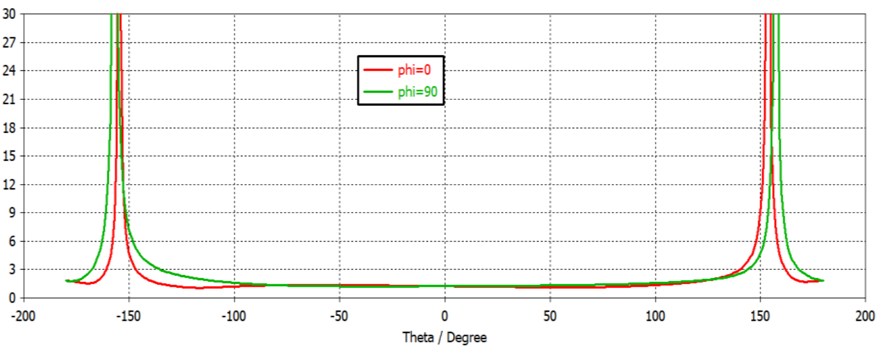


Figure 3.32. AR beam-width for 2.4 GHz, (a) for Phi = 0°, (b) for Phi = 90°.

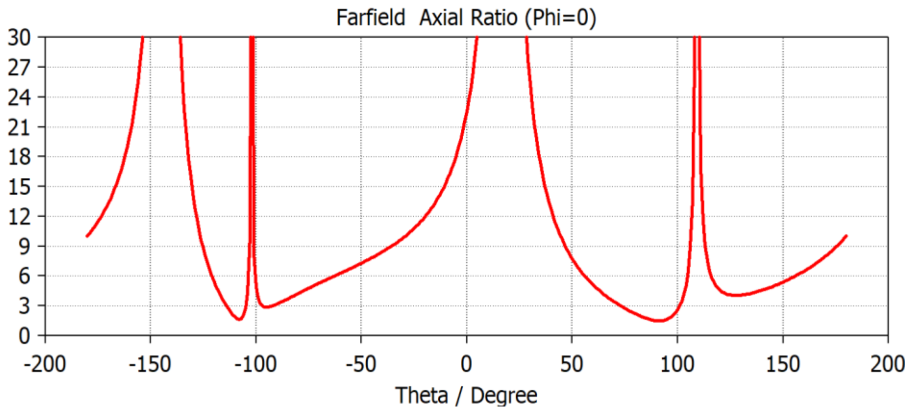


Figure 3.33.AR beam-width for 0.9 GHz for Phi=0.

Upon analysing the aforementioned findings, we have derived the acceptance results, which are presented in the table 3.2. Furthermore, as depicted in Figure 3.33, it is evident that we were unable to attain a CP in the ISM lower band.

Table 3.2: the AR beam-width for the acceptance results.

uency (GHz)	Phi = 0°	Phi =90°
GPS 1,575 GHz	[-90°,90°] covers 180°	[-50°,100°] covers 150°
ISM 2,4 GHz	[-150°,140°] covers 290°	[-135°,140°] covers 285°

From these results, we can say that the circular polarisation is obtained in the both GPS and ISM higher bands In contrast to the lower ISM band, which necessitates further optimization.

- **AR bandwidth:**

Figure 3.34 bellow represents the results of the AR bandwidth.

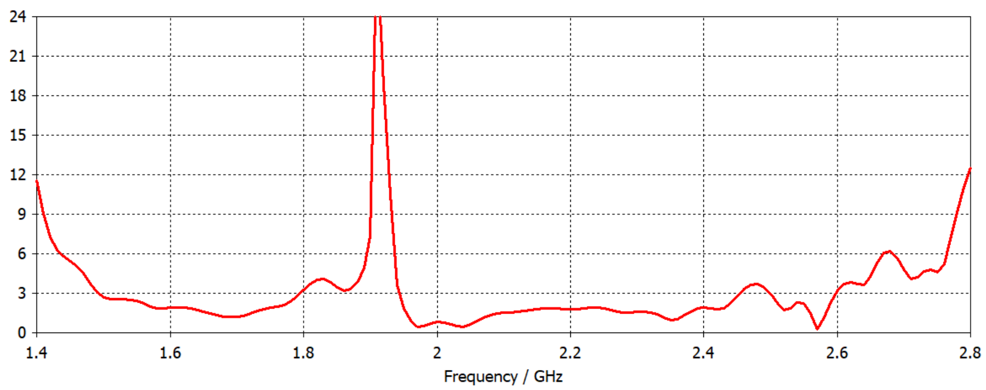
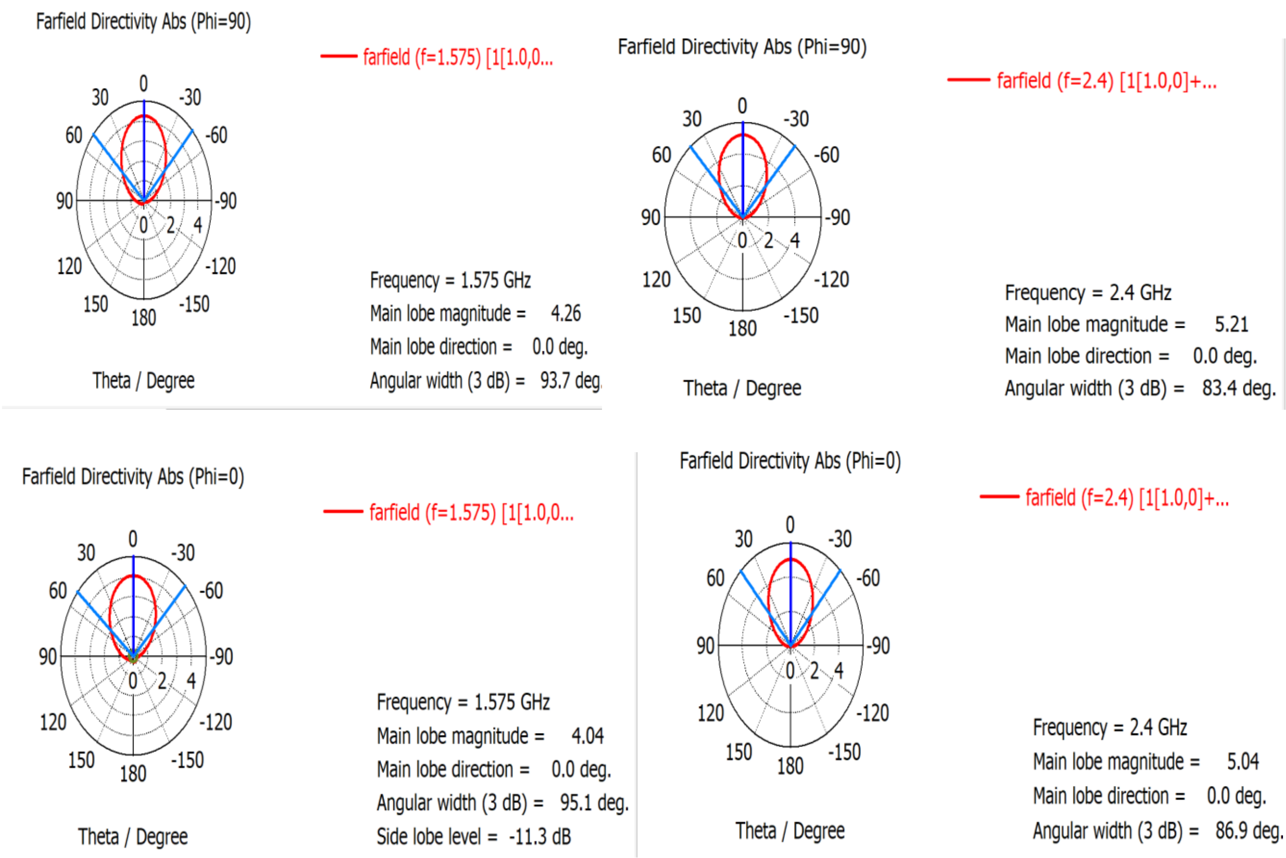


Figure 3.34. Simulated AR versus frequency of the proposed antenna.

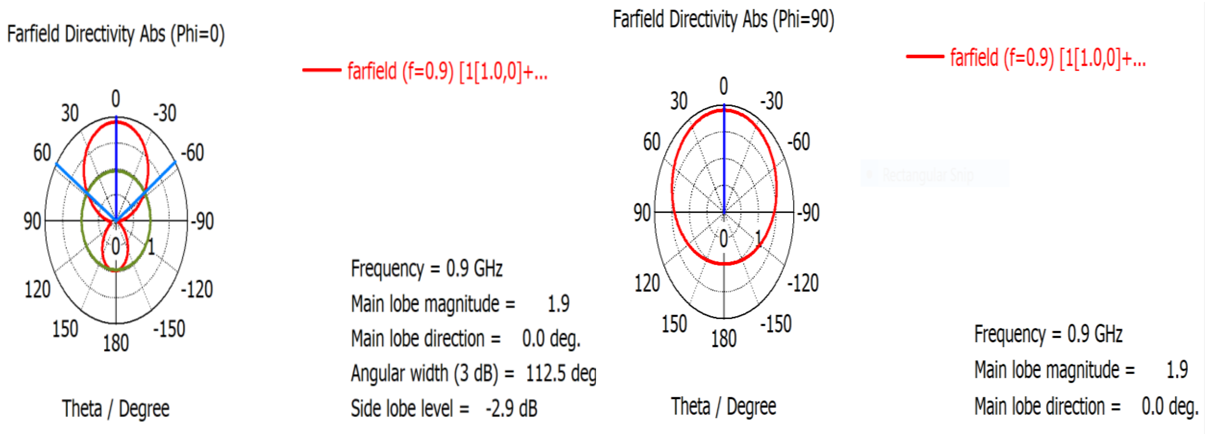
As evident from the observation, the bandwidth of the axial ratio (AR) remains below the 3 dB threshold in both frequency bands. This substantiates the successful achievement of circular polarization in both GPS and ISM higher band, and from the previous results we can assume that the AR band width still missed in the ISM lower band in view of the fact that this antenna need more configuration.

c. Radiation patterns

Figure 3.35 represents the radiation pattern in the two bands.



(a) (b)

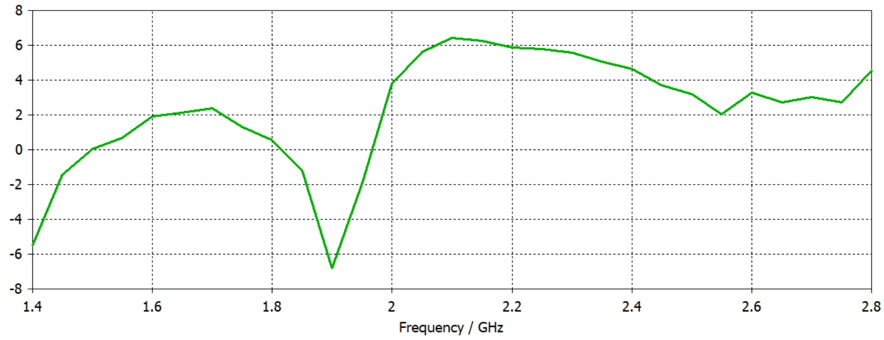


(c)

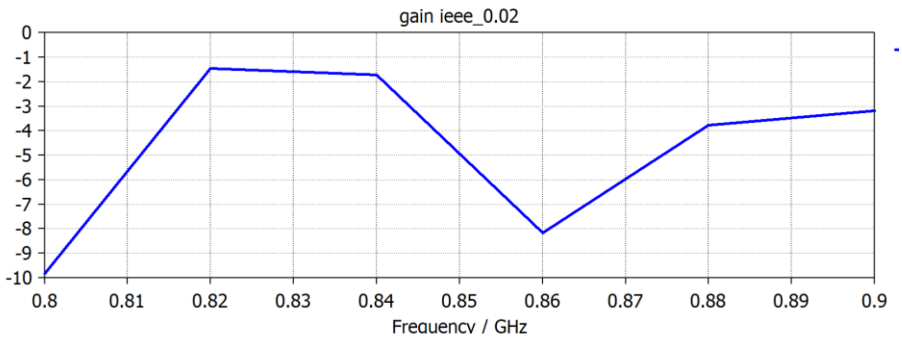
Figure 3.35. Radiation pattern, (a) for 1,575 GHz, (b) for 2,4 GHz, (c)for 0,902.

d. Gain

Figure 3.36 represent the gain in the tri-bands.



(a)



(b)

Figure 3.36. The simulated gain at bore sight, (a) for the GPS and ISM higher band, (b) for the ISM lower band .

The results are illustrated in table 3.3

Table 3.3: Gain results

Frequency (GHz)	0.902	1.575	2.4
Gain (dBi)	-3.5	2	5

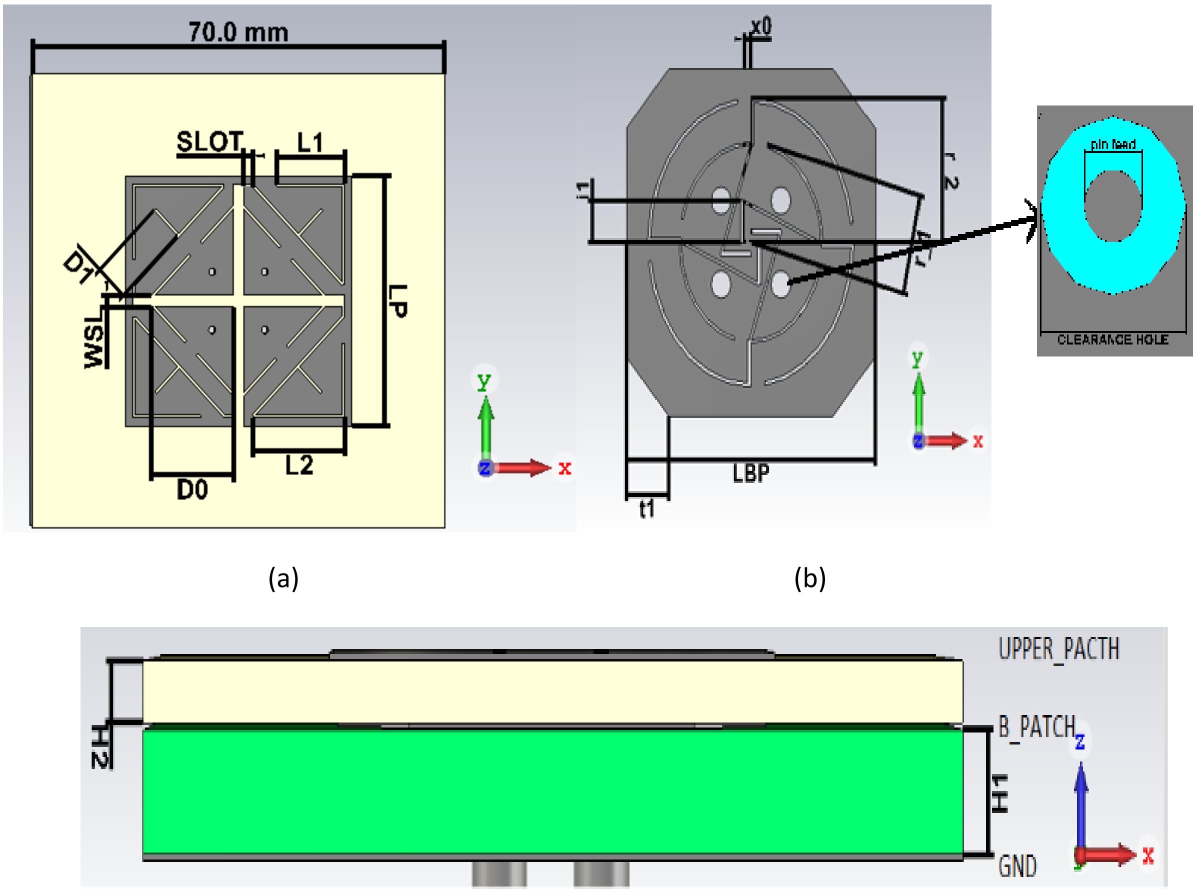
As indicated by the obtained results, the gain within the two bands manifests a positive value, the results shows that the antenna's gain is about 2 dBi at the first reference frequency and it's about 5 dBi at the higher ISM band 2.4 GHz expect for the lower ISM band 0.902 GHz. Thereby affirming the commendable performance of this antenna.

Consequently, it can be conclusively stated that this design unequivocally satisfies our specified requirements and, furthermore, exceeds them by providing a triple band circularly polarized antenna capable of serving multiple applications with exceptional performance characteristics.

3.3.7 Size configuration of the final design

In this section we can say that generally , in the stacked antennas configuration the coupling between the upper and the bottom patch effects on performance of the antenna, the parametrical study of each and every single slot's parameter and it wouldn't be sufficient due to the large number of the interacted parameter of the proposed antenna ; therefore we need to pay attention to all the performance at the same time with any parameter tuning , the optimization technique can be more advantageous and more effective in terms of the simulation duration as we can that we are close to get the required results with applied modifications .

Considering that all the desired specifications and performance metrics have been accomplished, it prompts contemplation of manipulating one final parameter. This entails a reduction in the dimensions of the structure from 80x80 mm^2 to 70x70 mm^2, as shown in figure 3.37.following by parameters table.



(a) (b)

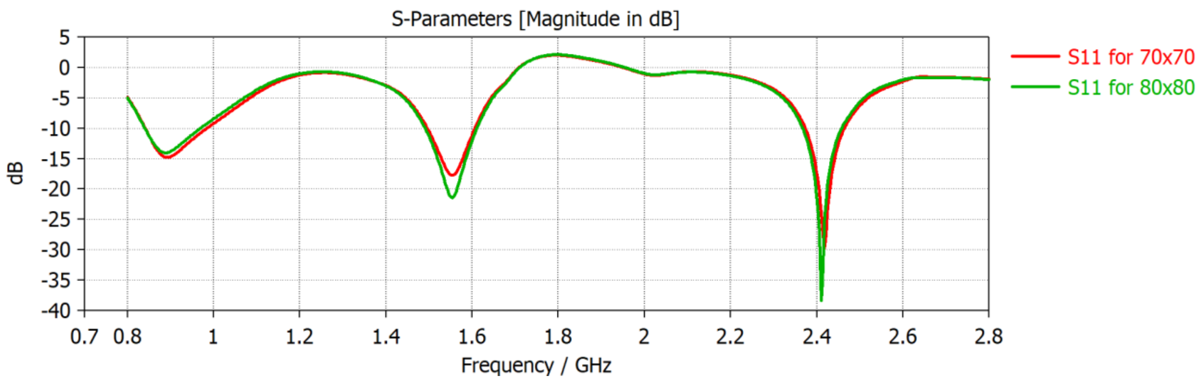
(c)

Figure 3.37. Antenna final design with 70x70 mm²structure, (a)front view ,(b) bottom view, (c) side view.

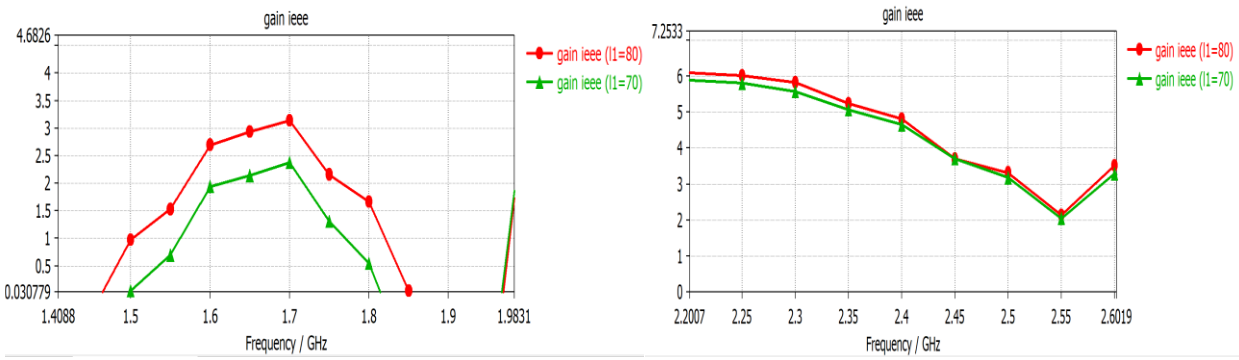
Table 3.4: Dimension of the proposed antenna (in millimetres)

parameter	L1	LP	LBP	L1	L2	WL	WSL	D0	D1	WD1
value	70	38.6	33.8	10.5	15.5	0.4	1.8	13.9	5.5	0.5
parameter	SLOT	T1	x0	R1	WR	R2	I1	TAB		
value	1.6	9	1.5	10.8	0.5	15.5	2	2		

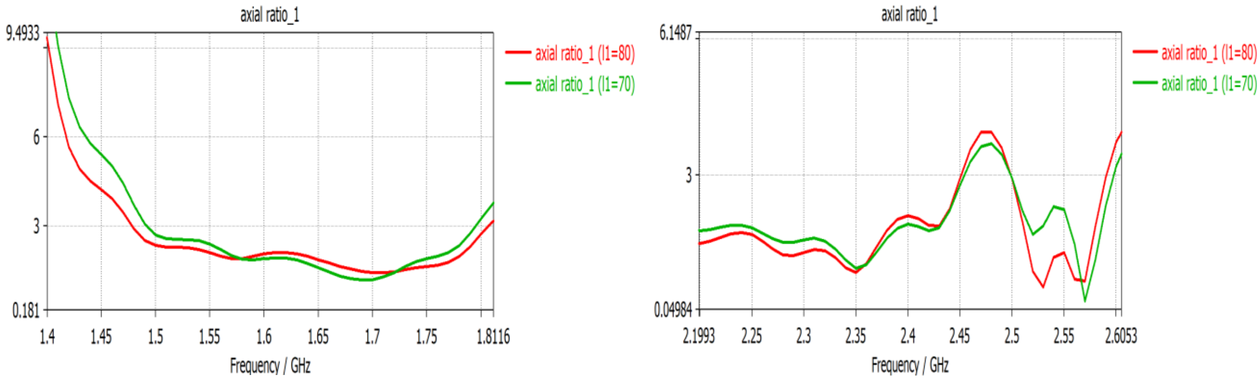
The comparative analysis of outcomes is visually presented in the subsequent section, providing a comprehensive depiction of the contrasting results obtained.



(a)



(b)



(c)

Figure 3.38. The final results, (a) S11, (b) Gain, (c) axial ratio bandwidth.

Upon careful observation, it is evident that the results obtained from the 70x70 mm^2 antenna are remarkably similar. The tri-band capability, circular polarization, and fulfilment of other specifications are still achieved with notable success. Based on these findings, we can confidently adopt the 70x70 mm^2 antenna as the ultimate and definitive design solution.

3.4 Comparison of the proposed antenna with prior art

The comparative analysis shall be elucidated in the format of Table.

Table 3.5: comparison of the proposed antenna with prior art.

ref	Size (mm^3)	Freq band (GHz)	S11<-10 dB (band)	3-AR band-width (GHz)
[33]	80x80x4.6	1.1764 1.5759	dual	1.0/1.2
[34]	100x100x15	[1.40-1.45] [2.38-2.48]	dual	0.7/1.2
[35]	Circular R= 15,5	[2.4-2.48] [5.735-5.875]	dual	0.2/0.6
[36]	50x50x3.27	[3.45-3.55] [5.7-5.9]	dual	1.0/3.1
Our work	70x70x9.6	[1.5-1.6] [2.38-2.48] [0.84-0.98]	triple	1.5-1.8 1.95 -2.48

This table shows a comparison between our work and similar previous works. The other endeavours cover two frequency bands, while our work covers three. Additionally, our project is smaller in size compared to most of these other works. Because of these reasons, we can confidently say that our antenna is a competitor to these endeavours.

3.5 Conclusion

This chapter deals with the design of a circularly polarized stacked patch antenna that can cover three operating frequency bands: radio-navigation and ISM (lower and higher bands). Following the presentation of this antenna, its performance was assessed and the desired specifications were successfully met, however, it is obvious that the third band ISM lower [902-928] MHz still require some optimisations. Upon comparing this work with other relevant research works, it can be deduced that this project boasts numerous advantages namely triple band behaviour, circular polarization and finally compact size.

General conclusion

This work focuses on the design of a triple-band circularly polarized patch antenna, encompassing various aspects of antenna engineering. The first chapter provided an overview of antennas, starting with a comprehensive discussion on their definition, historical background, and key characteristics. A specific emphasis was placed on patch antennas, highlighting their widespread use and advantages in modern communication systems.

The second chapter delved into multiple band techniques and circular polarization technique, presenting a scientific review of existing research and advancements in the field. This segment elucidated the significance of achieving multiple frequency bands and circular polarization for enhanced performance and versatility in antenna applications.

The third and final chapter of this study was dedicated to the design and simulation of the triple-band circularly polarized patch antenna that covers both lower and higher ISM (0.902-0.928) GHz (2.4-2.48) GHz respectively and GPS (1.563-1.587) GHz, frequency ranges. This section meticulously detailed the step-by-step engineering techniques employed in the antenna's development which is represented in the combination of different techniques of circular polarization (four pin feed access, trimmed, annular rings ...) and multiple band (stacked technique, slots ...), including the selection of materials, dimensions, and feeding techniques. Additionally, a comprehensive comparison was conducted with other relevant works in the literature, highlighting the strengths and uniqueness of the proposed design.

Overall, the study offered a comprehensive exploration of the design and simulation process of a triple-band circularly polarized patch antenna. By providing a thorough background on antenna generalities, discussing multiple band and circular polarization techniques, and presenting a detailed engineering approach, the study contributed to the advancement of antenna technology and its applications in modern communication systems.

The perspectives of this study summarize in adding some optimization in the third band, ISM (0.902-0.928) GHz, by improving the gain and axial ratio. Secondly, the realization of the designed antenna through fabrication and measurement is important, by comparing the obtained results with the simulated ones, the accuracy and effectiveness of the design can be validated. Finally, we are looking forward that the findings and contributions of this work will be disseminated to the scientific community. Publishing the results as a research paper in a reputable conference will enable wider recognition, facilitate knowledge sharing, and foster further collaboration in the field of antenna design and telecommunication systems engineering.

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Appendix

BRIEF PRESENTATION OF CST MICROWAVE STUDIO

A.1 Summary presentation

Founded in 1992, the electromagnetic simulation software CST MICROWAVE STUDIO (CST MWS) is the culmination of many years of research and development in the most efficient and accurate computational solutions for 3D electromagnetic designs.

CST Microwave Studio is a popular electromagnetic simulation software developed by Computer Simulation Technology (CST), a leading provider of electromagnetic simulation software solutions. It is widely used by engineers, researchers, and scientists for the design, analysis, and optimization of high-frequency and microwave components, devices, and systems [37].

It uses the finite integration technique (FIT) to solve Maxwell's equations numerically. It allows users to model and simulate a wide range of electromagnetic phenomena, including antennas, waveguides, filters, connectors, transmission lines, RF/microwave circuits, radar systems , and more. CST Microwave Studio offers advanced features like parametric studies, optimization algorithms, and co-simulation capabilities with other CST software products, allowing users to explore design alternatives, optimize performance, and integrate their microwave designs into larger systems [38].

In order to address all simulation demands related to the field of electromagnetics, CST has over a dozen numerical solvers. These solvers are specifically tailored for different domains: there are temporal and frequency-domain solvers for high and low frequencies, an integral and asymptotic solver for large structures, as well as other solvers such as Multiphysics solvers (thermal and fluidic) and a static solver. Figure A.1 illustrate the main interface of CST [37].

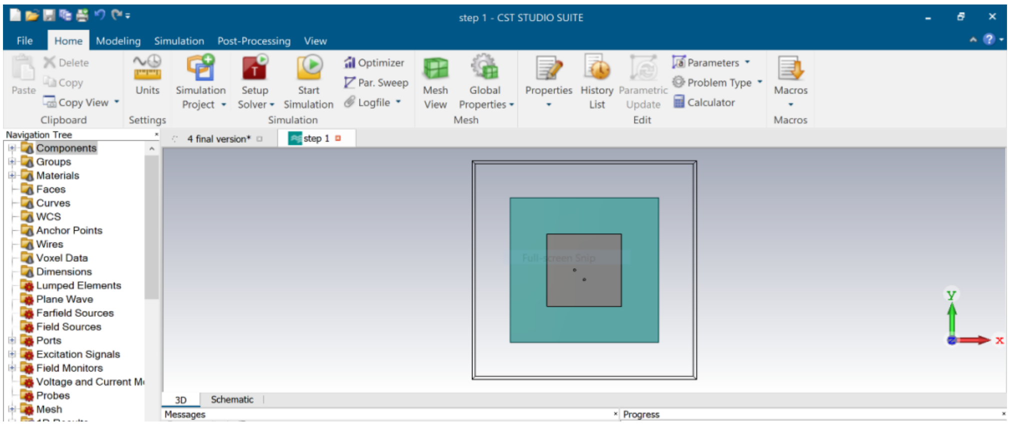


Figure A.1. The main interface of CST MICROWAVE Studio.

A.2 Simulation example

➢ **Create a new project**

After launching CST DESIGN ENVIRONMENT, we choose to create a new CST MICROWAVE STUDIO project (figure A.2). Then, we select the environment in which the structure will be created (figure A.3) .and the antenna type (figure A.4).

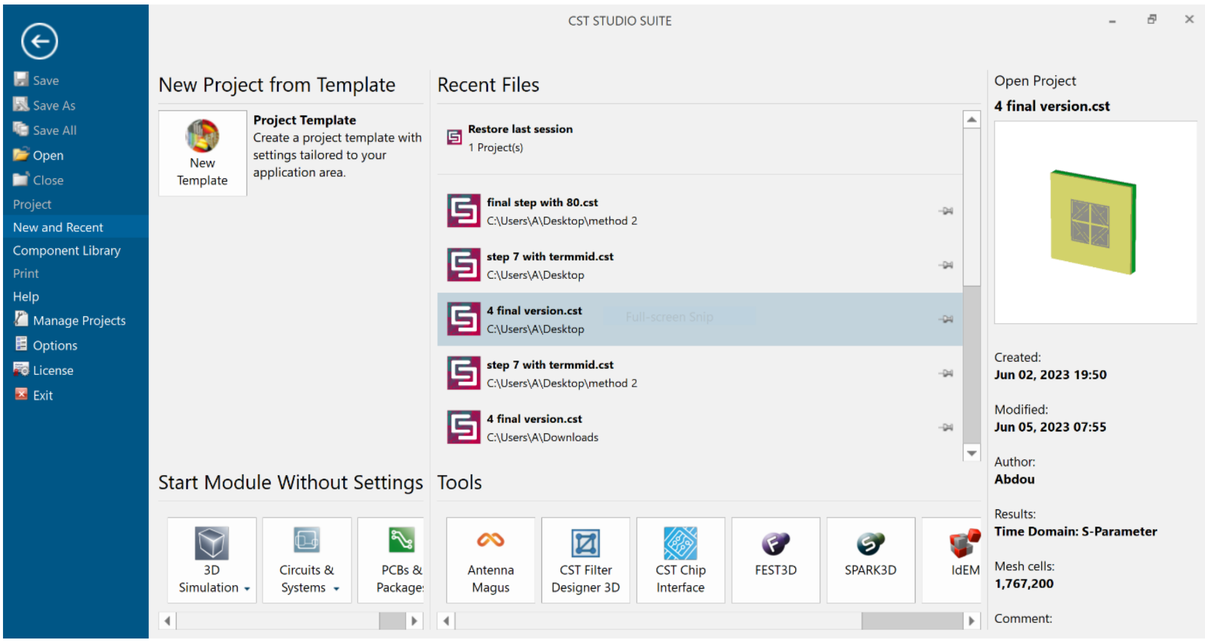


Figure A.2. Create a new project.

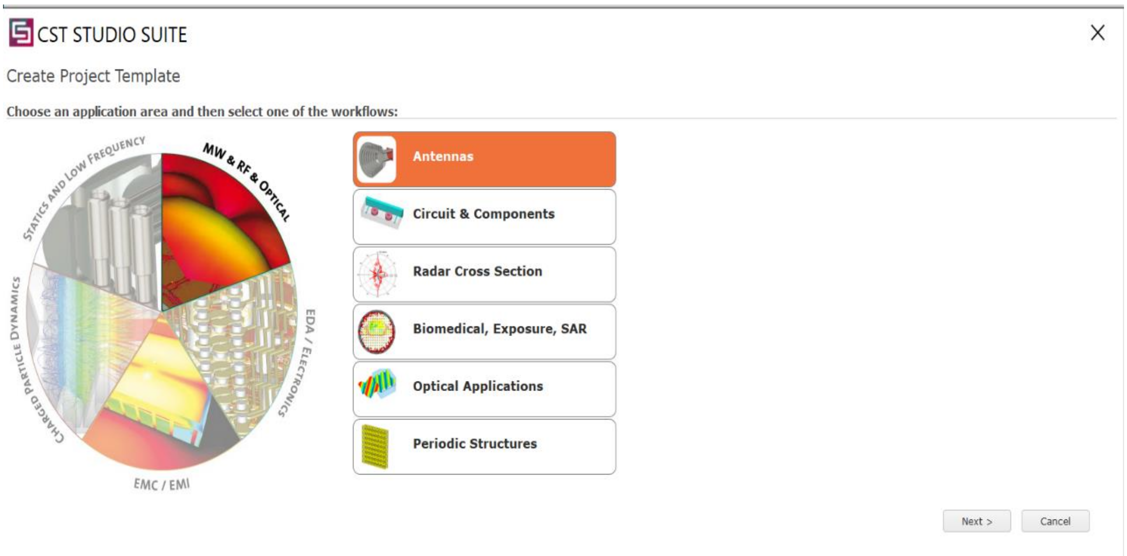


Figure A.3. Choice of environment.

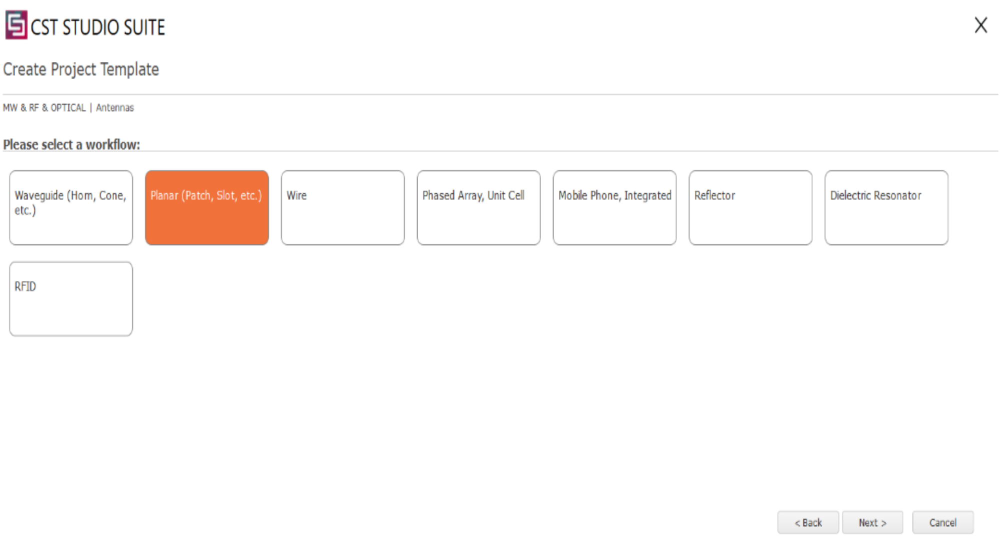


Figure A.4. Choice of antenna type.

➢ Units definition

We select the units of dimensions, frequencies, time, and temperature… for the parameters of our antenna (Figure A.5).

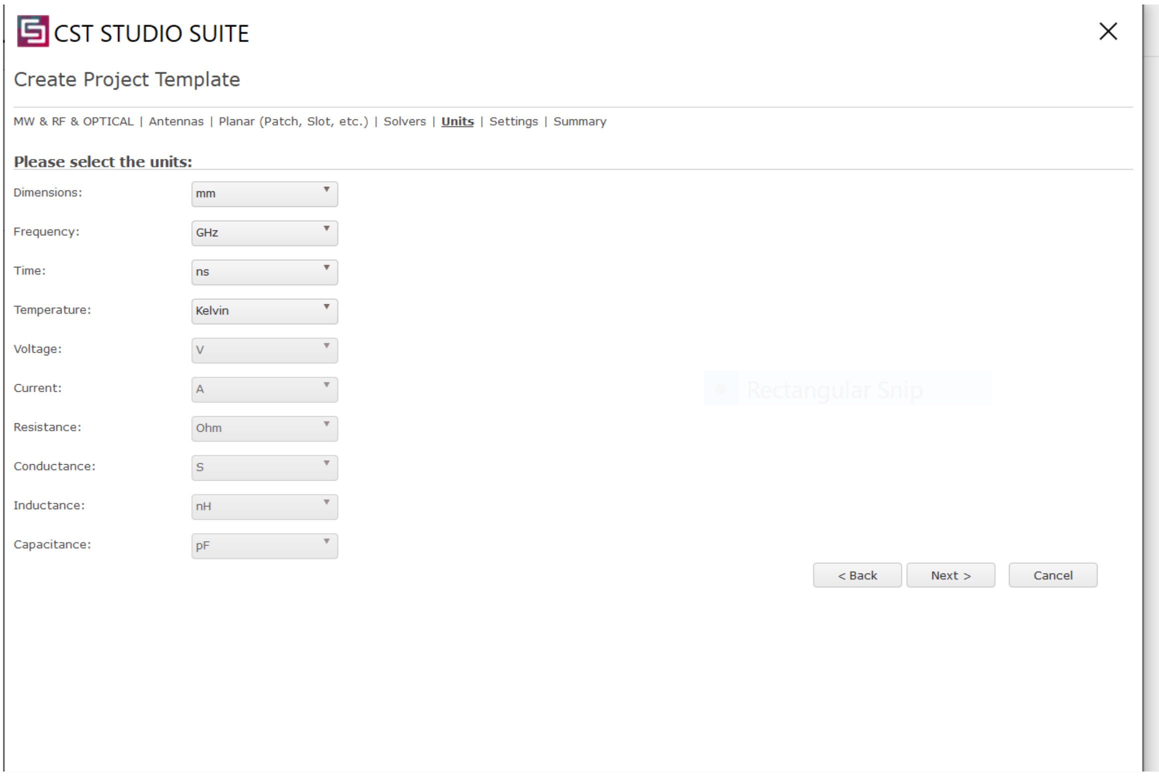


Figure A.5. Unites definition.

➢ **Definition of the frequency range**

We select the frequency range in which we analyse the problem (Figure A.6). We can also specify the frequency range by choosing simulation ➡Frequency from the main menu.

Figure A.6. Definition of the frequency range.

➢ Structural modelling

There are several different geometric design tools for typical geometries such as boards, cylinders, spheres, etc., for modelling the antenna structure (ground plane, substrate, feeding line, and radiating element). These shapes can be added or subtracted using Boolean operators to construct more complex shapes. An example in figure A.7.

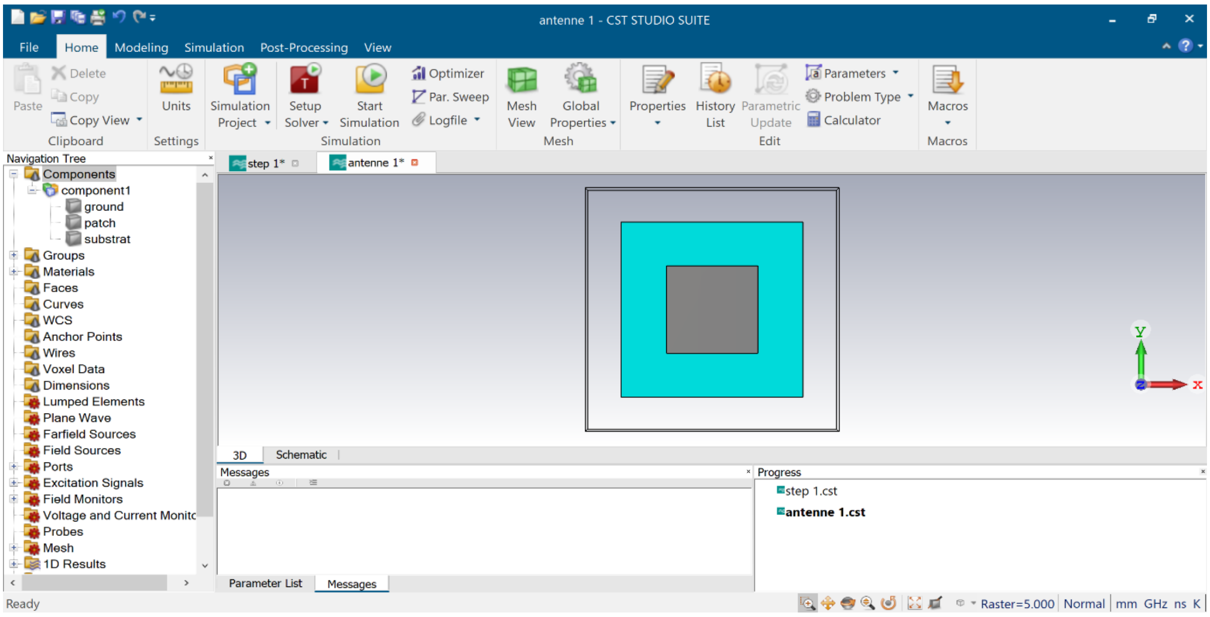


Figure A.7. Design of structure to simulate.

➢ Coaxial feed modelling

The last modelling step is the construction of the coaxial feed as the excitation source for the micro-strip patch antenna (Figure A.8).

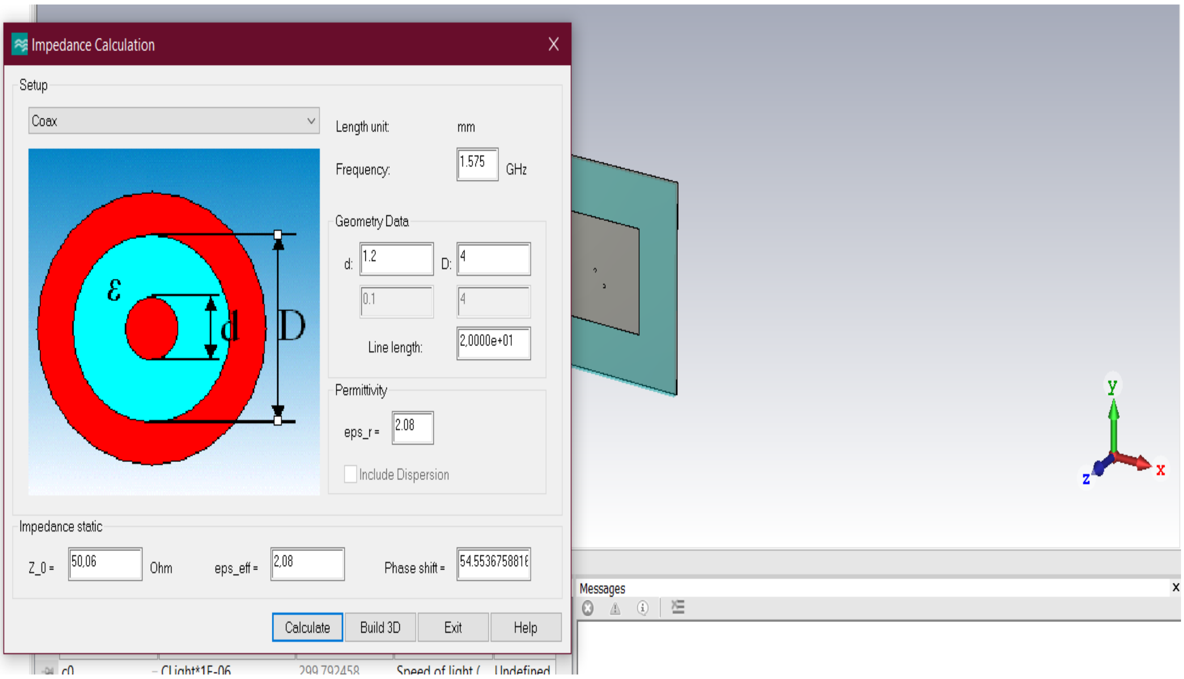


Figure A.8. Design of structure connected with coax.

➢ Definition of port:

Finally, the last step is the excitation of the patch antenna with a port before the calculation and resolution phase of the electromagnetic problem. The waveguide port is used to excite structures such as the rectangular waveguide or simulate a connector (connected to a coaxial cable) that is connected to the antenna structure at the feeding line (Figure A.9).

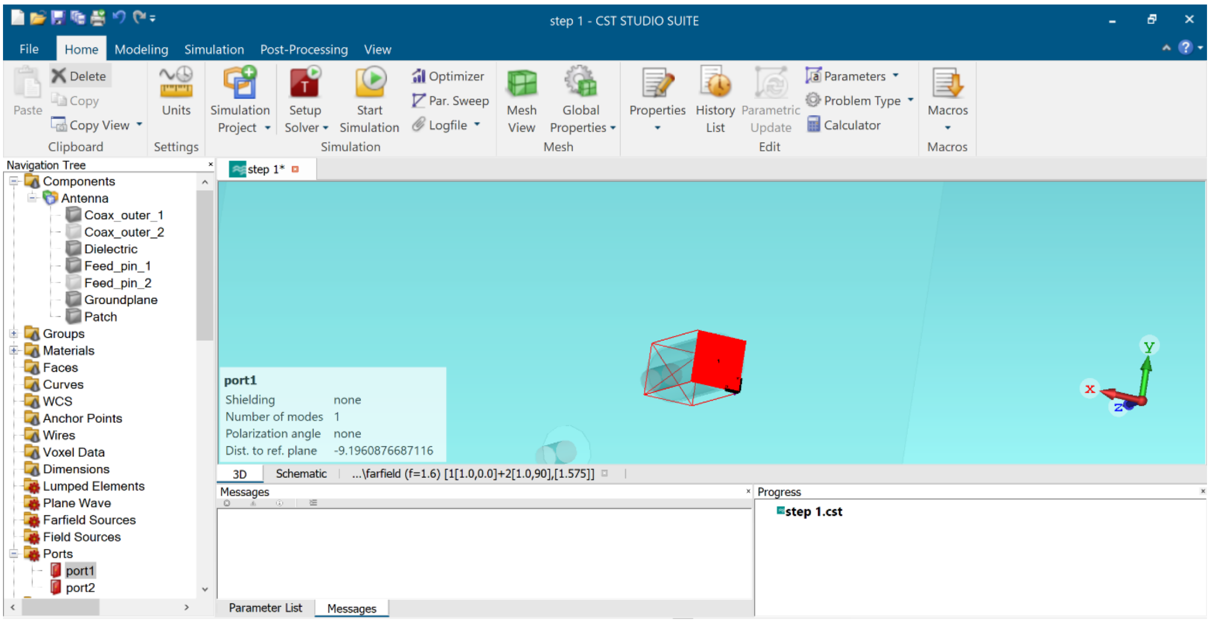


Figure A.9. Application of the excitation port (in red).

➢ Simulation start:

After defining all the necessary parameters, we are ready to begin our first simulation. We initiate the simulation by selecting the time domain solver from the main menu: Home ⇒Setup Solver ⇒ Time Domain Solver.

➢ Displaying the results:

After successfully running a simulation, numerous results are available. We simulated a structure of a rectangular patch with CST.

The different graphs that we can visualize, such as the reflection coefficient, the Smith chart (Figure A.10), and the 2D radiation pattern (Figure A.11) and 3D radiation pattern (Figure A.12), are shown below.

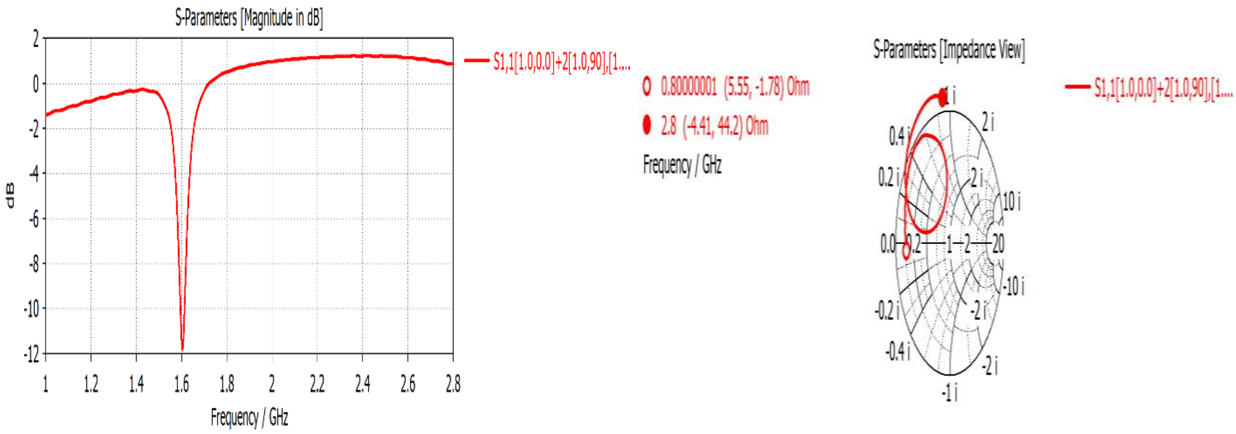
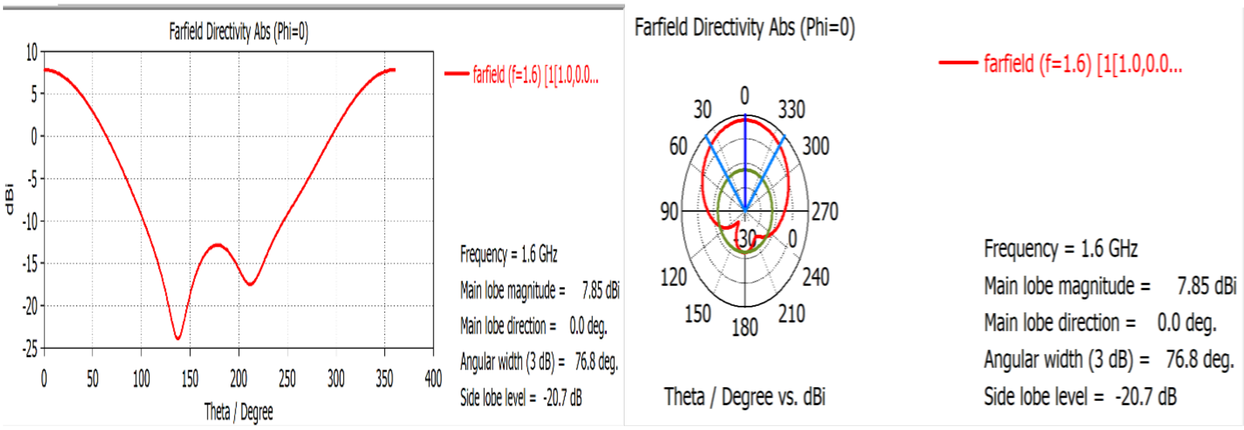


Figure A.10. Reflection coefficient S11 and Smith chart.



(a) Cartesian form (b) polar form

Figure A.11. 2D radiation pattern.

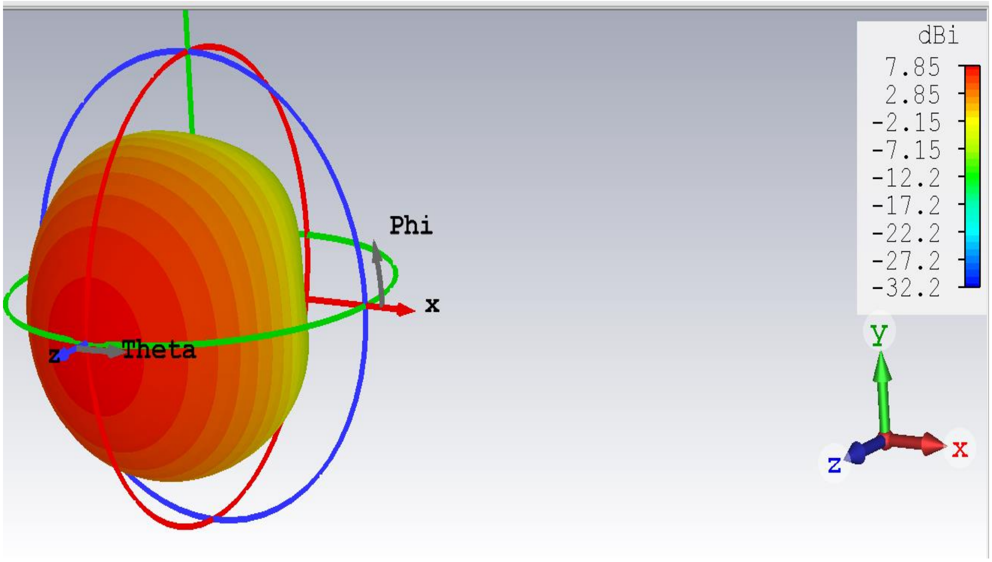


Figure A.12. 3D radiation pattern.